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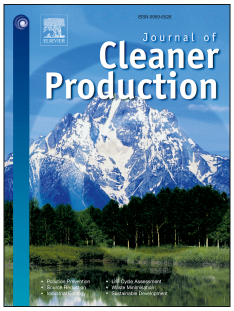

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Anticipatory Life Cycle Assessment of sol-gel derived anti-reflective coating for greenhouse glass

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Keywords: Anticipatory LCA, scenarios, scale-up, greenhouse glass, anti-reflective coating, dip coating

Abstract

Environmental analysis should be performed early in the Research and Development (R&D) phases of new technologies to timely determine potential impact and, thereby, include prevention and minimization of unfavorable ecological impact into the innovation process. Here, we demonstrate the application of anticipatory Life Cycle Assessment (LCA) on novel anti-reflective coatings used for greenhouses in the Netherlands. Currently, these coating technologies are developed at the laboratory scale (lab-scale), but they have the potential to be transferred to commercial scale on the short term. What-if scenarios have been used to scale-up the coating production process to pilot and industrial scales. The scenarios were developed by optimizing the laboratory scale coating production parameters. A cradle-to-grave LCA has been done to compare novel coatings with conventional coatings. The functional unit has been defined as the production of 1692.30 kg of tomatoes in greenhouses during 30 years. Results indicate that the novel coating manufactured at industrial scale can compete with conventional coatings in terms of the environmental performance. Furthermore, LCA shows that the novel coating assessed does not bring environmental benefits as compared to employing uncoated glass. However, the use of the glass coating in the greenhouse may bring economic benefits during functional lifetime by means of increased yield of crop (e.g. tomatoes). Different pathways of the technological development of the novel coating have been considered in the sensitivity analysis. The option that includes glass manufacturing in the Netherlands rather than China has led to the best environmental impact results.

Highlights

1. LCA was used to guide coating innovation towards decreased environmental burden
2. Scenarios were used to scale-up coating production from lab-scale to larger scales
3. The LCA results of novel and conventional coatings were within the same magnitude
4. Change of the location for the glass production significantly affected LCA results

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1. Introduction

Technological innovation without doubt brings advantage to society and the quality of life. However, at the same time, it may induce unfavorable impact to both the environment and society. David Collingridge (1980) pointed to the control dilemma that a technology can be easily adjusted in its early development stages, but then the knowledge on its full impacts is still lacking. This has led to the development of technology assessment aiming at systemically identifying adverse impact (e.g. Van den Ende et al, 1998) and, more recently, the concept of responsible innovation (Grunwald, 2014). Ideally, there should be `… a growing awareness of the need to innovate, but to innovate responsibly' (Owen et al., 2009). Several research efforts call for the changes in agency regarding the ways of how science is being developed (Gibbons et al., 1994; Gorman et al., 2004; Fisher et al., 2006). Risk identification at the early phase of Research and Development (R&D) is one of the most important actions for the prevention of undesirable consequences (Sutcliffe, 2011). Methods for quantifying the environmental impacts of technologies should be used in the avoidance of possible environmental issues. However, environmental assessment has not been effectively practiced early in R&D phases. Technology development without consideration of possible environmental impacts can be problematic due to at least three reasons (Wender et al., 2014):

1. Most of the environmental impacts of innovations can be locked in by early R&D decisions (Bhander et al., 2003, Collingridge, 1980).
2. There is lower possibility to transform the technology development towards its better environmental performance in the later phases of the development (Stilgoe et al., 2013).
3. Environmental regulations are commonly applied in retrospect (Owen and Goldberg, 2010).

Life Cycle Assessment (LCA) has been proposed as a framework for the environmental assessment in Responsible Research and Innovation, but it still needs to overcome some hurdles. Regular LCA cannot be used directly in the analysis of innovation. Initially, it was designed with the purpose to evaluate the environmental impacts of existing technologies, and, therefore, it is retrospective by definition (Villares, et al., 2017). Modifications have been added to the LCA procedure by a number of scholars to enable the assessment of emerging technologies. Those approaches include the use of different up-scaling techniques to make it possible to evaluate a technology at pilot or commercial scale (Arvidsson and Molander, 2017; Tsang et al., 2016; Piccinno et al., 2016). Advances fall under prospective, ex-ante and/or anticipatory LCA, all which cater to new technologies (see Cucurachi et al., 2018).

In the work described, we employ the anticipatory LCA approach as defined by Wender et al. (2014). Specifically, we apply anticipatory LCA for the evaluation of a novel greenhouse glass coating technology. The goal of the study is to assess coating technology options in the R&D phase in order to move towards improved environmental performance and provide recommendations to the technology developers. Few LCA studies on glass coatings have been carried out, e.g. LCA of the nano coating which gives self-cleaning property to float glass (Pini et al., 2016) and LCA of solar selective coatings (Sánchez-Cruces et al., 2014). To the best of our knowledge, this is the first work that assesses a new type of specifically anti-reflective glass coating for greenhouses.

1.1 Case study

Greenhouse horticulture is one of the technologies that will provide sufficient, sustainable and good quality food and ornamental plants for the global population in the future (Holland, 2016). The Netherlands is a world-leader in the greenhouse horticultural sector, producing 24% of the world trade of horticultural products (horti daily, 2016). For instance, the Netherlands is the second largest exporter of tomatoes in the world (Phillips, 2016). For this LCA study, production of tomatoes under different types of greenhouse glass will be considered as the function in the modelling, as tomatoes are the most commonly grown type of crop in Dutch greenhouses.

In the Netherlands, a country where there is a low intensity of natural light, particularly in winter season, it is essential for greenhouses to have the maximum possible light transmittance. Light intensity is one of the most important factors for crop yield. It was reported that the increase of light by 1% results in a plant yield gain of 0.5% to 1% for most of the greenhouse crops (Marcelis et al., 2005). One of the problems in the greenhouses, is that part of the light is not transmitted due to reflections on the glass-air interfaces.

Anti-reflective coatings are glass coatings which reduce the reflectivity of glass, thus allowing greater amounts of light to be transmitted inside the greenhouse. It was reported that the use of anti-reflective coatings results in an increased light transmittance by 6.2% which leads to the gain of the tomatoes yield by 8.4% (Hemming et al., 2009). Uncoated greenhouse glass (low iron glass) and glass manufactured by acid etching and sputtering methods will serve as the reference data. In this work, they will be referred to as “Uncoated glass”, “Acid etching”, and “Sputtering”, respectively. Uncoated glass was included as a reference in this LCA work in order to see if there is an advantage of using anti-reflective coatings from the environmental point of view as their performance will be compared based on the amount of tomatoes produced under a greenhouse glass. Acid etching and sputtering methods were chosen as the references, as those are the techniques used in the production of anti-reflective coatings for greenhouse glass at industrial scale (Hemming et al., 2009).

Different yield of tomatoes can be obtained under uncoated and coated greenhouse glass. The mass of tomatoes produced in the Dutch greenhouse covered by uncoated structured glass with the light transmittance of 90.30% equals to 54.00 kg/m^2/yr (Hemming et al., 2009). The mass of tomatoes obtained in 30 years under Uncoated glass is 1620.00 kg/m^2. The light transmittance of acid etching and sputtering is 96.50% (Hemming et al., 2009) for the first 10 years of use. After 10 years, they start to lose their anti-reflective property gradually each year. In the LCA modelling, it was assumed that there was the same percent change for the yield of tomatoes produced as for the light transmittance (Marcelis et al., 2005). In the thirtieth year, they have the same light transmittance as Uncoated glass 90.30% (tomato yield equals to 54.00 kg/m^2). The tomato yield for coated glass (Acid etching and Sputtering) in 30 years was calculated to be 1692.30 kg/m^2. Figure 1 shows the yield of tomatoes obtained under uncoated and coated greenhouse glass in 30 years.

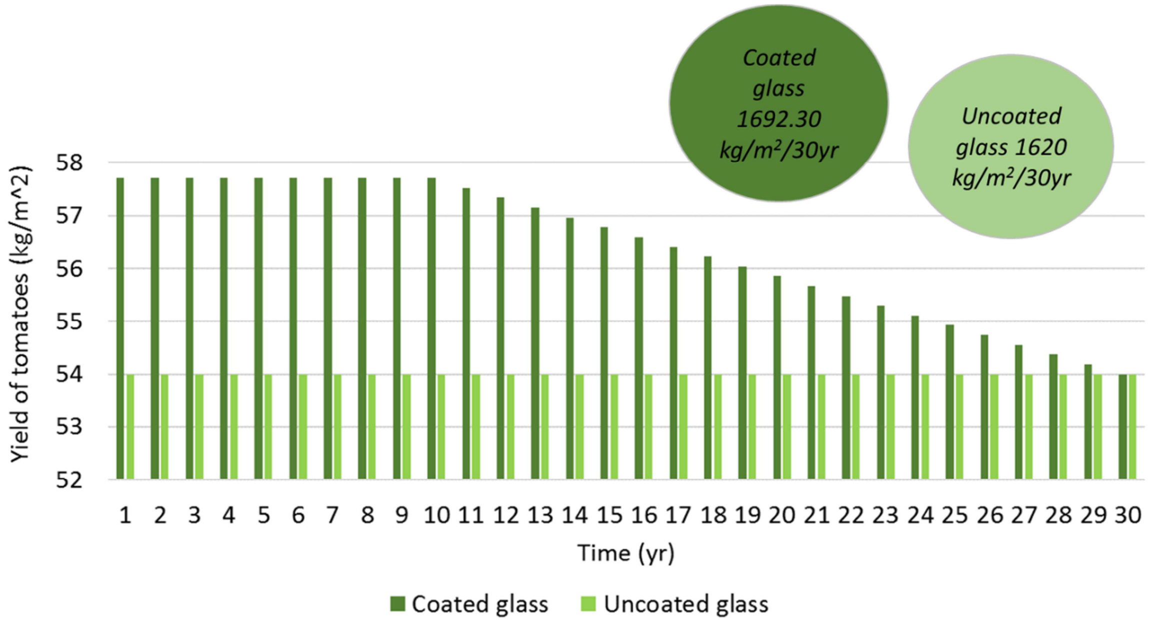

Figure 1. Annual yield of tomatoes grown under 1m^2 of uncoated/coated greenhouse glass during 30 years glass lifetime. The bubbles represent the total production of tomatoes under each condition.

Currently, sol-gel derived anti-reflective coating is being investigated as an alternative to glass coating by acid etching and sputtering. The greenhouse glass covered with sol-gel coating will be referred in this paper to as "'Dip coating" (the glass with a new coating (sol-gel) produced by application technique "dipping"). The sol-gel coating is composed of silicon dioxide nanoparticles (SiO_2) which are produced using ethanol as a solvent. It is expected that the advantages of Dip coating over Acid etching and Sputtering will be increased light transmittance of 99% and decreased degradation time. Also, given the simplicity of the process (no complex equipment is required), it is expected that Dip coating can become a cost competitive alternative to Acid etching and Sputtering. For baseline comparison, it will be assumed that the same amount of tomatoes could be obtained under Dip coating as under Acid etching and Sputtering (1692.30 kg/m^2/30 yr). Sensitivity analysis will be done assuming that the performance characteristics of Dip coating (increased light transmittance and decreased degradation time of a coating) would be achieved. Table 1 contains the description of the coatings used in this study.

Table 1. Description of Dip coating and the references.

Alternatives	Production methods	Production scale	Light transmittance (T) and degradation time
Dip coating	Sol-gel anti-reflective coating is produced by dipping the glass into solution of polymeric inorganic precursors (Brinker, 1991). The coated glass is dried, and then cured at 400°C for 1 hour in the oven. The coating method is mostly used at laboratory scale but has been started to be implemented at industrial scale.	Laboratory scale	T=96.50%; Degradation time after 10 years (Expected parameters: T=99.00%; Degradation time after 30 years)
Uncoated glass	The production of flat glass is divided into the processes such as raw material feed, melting, patterning, and annealing (AGC, 2012).	Industrial scale	T=90.30%; Degradation time after 30 years
Acid etching	The glass is immersed into the bath filled with fluosilicic acid solution, pulled out, and then rinsed with water (Pastirik, 1980).	Industrial scale	T=96.50%; Degradation time after 10 years
Sputtering	A special type of sputtering method called 'Reactive Sputtering' is used to produce silica coating on the glass surface. In this technique, oxygen gas is introduced into the inert argon environment. It reacts with the silicon atoms eroded from the target during the coating formation on the substrate (Monaco, 2016).	Industrial scale	T=96.50%; Degradation time after 10 years

2. Methodology

2.1 Goal and scope definition

The goal of the research was to guide R&D of the novel coating technology towards improved environmental performance based on the anticipatory LCA impact results. The geographical coverage for this LCA study includes China where the glass for the greenhouses is usually produced and the Netherlands where significant amounts of greenhouses are located. The time boundary spans 30 years (including winter and summer seasons). A cradle-to-grave approach was used in this study as this allows to reveal hotspots through the whole life-cycle of the product system. The foreground processes for the product systems of the coatings were modelled using literature and in-house data, as well as data from companies including Poot Kasdekreiniging and Van der Waay. The background processes were based on the ecoinvent v2.2 database developed by the Swiss Centre for Life Cycle Inventories (Frischknecht et al., 2005). The LCA follows ISO 14044 framework (2006), but is extended with what-if scenarios to scale-up the coating system to the pilot and the industrial scales.

CMLCA software (version 52) (CML, 2015) developed by the Institute of Environmental Sciences (CML) at Leiden University was used for the LCA calculations. The family CML 2001 Baseline, reference World, 2000 impact assessment (Guinée et al., 2002) was used as a mid-point method. Nine impact categories were considered in this study: 'Land use, competition', 'Eutrophication', 'Acidification', 'Photochemical oxidation', 'Climate change', 'Terrestrial ecotoxicity', 'Freshwater aquatic ecotoxicity', 'Stratospheric ozone depletion', and 'Human toxicity' (Guinée et al., 2002).

The function of the product system was to produce tomatoes in greenhouses during 30 years. The functional unit was defined as the production of 1692.30 kg of tomatoes in greenhouses during 30 years. The reference flow was the production 1692.30 kg of tomatoes in greenhouses under 1.04 m^2 of Uncoated glass/1 m^2 of Acid etching/1 m^2 of Sputtering/1 m^2 of Dip coating during 30 years.

2.2 System description

Figure 2 shows the flowchart for the greenhouse glass (Dip coating) product system. The detailed flowchart for the unit process “sol-gel coating production” and the flowcharts for the product systems of Uncoated glass, Acid etching, and Sputtering are shown in Appendix.

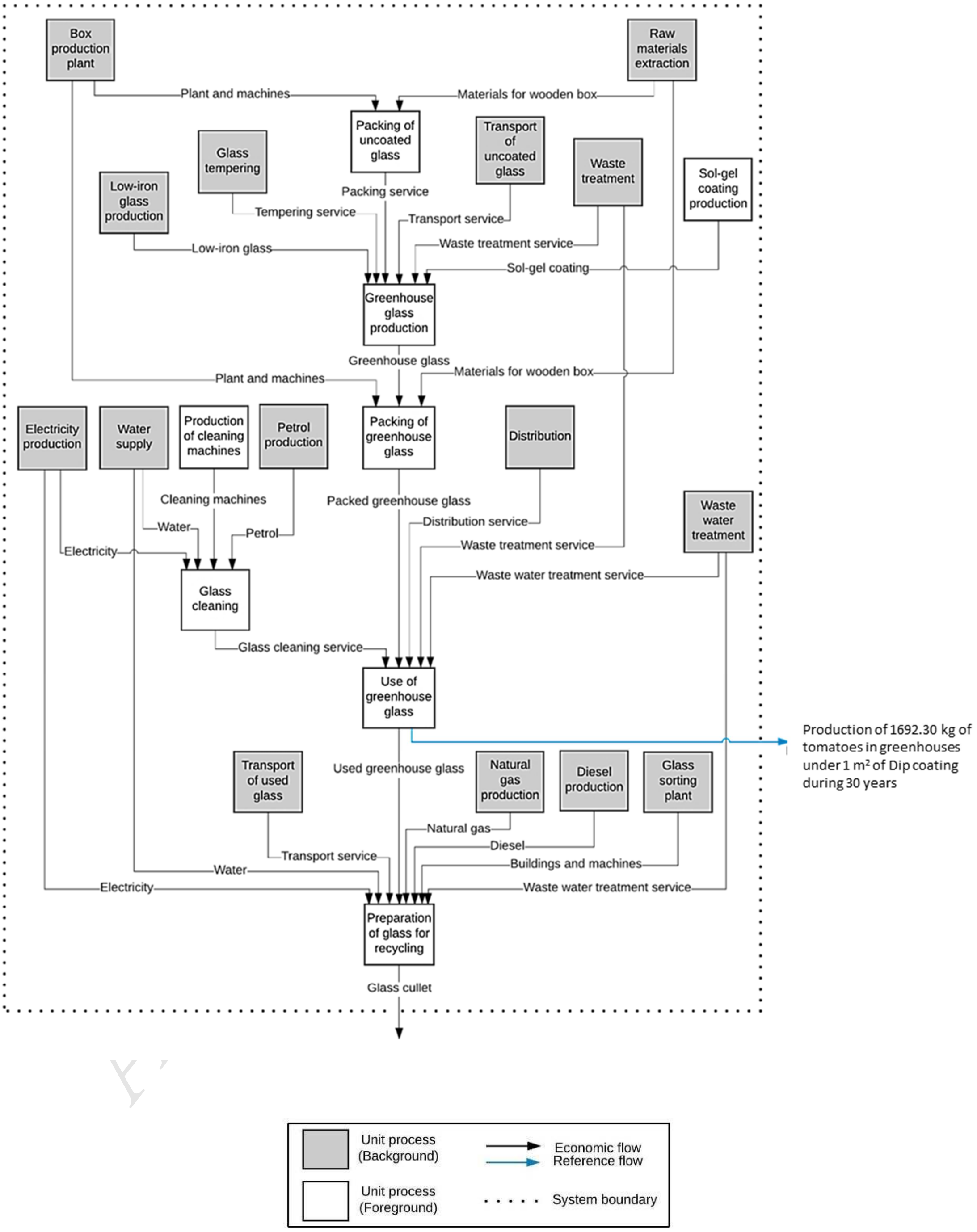

Figure 2. Flowchart for Dip coating product system

The product system of Dip coating can be divided into three main processes: production of greenhouse glass, use of the glass in greenhouses, and preparation of used glass for recycling. In this section an overview of these processes is given.

2.2.1 Production of greenhouse glass

2.2.1.1 Low-iron glass production and tempering

Diffuse (structured) low-iron glass is one of the commonly used types of glass used in greenhouses in the Netherlands (DutchGreenhouses, 2018). It was assumed that this type of glass was used in the production of greenhouse glass Dip coating. (The same assumption was made for Uncoated glass, Acid etching, and Sputtering). In this LCA study, low-iron solar glass was considered to be as a proxy for structured low-iron glass as the production for structured glass was not reported in ecoinvent v2.2. In particular, the ecoinvent v2.2 process *Solar glass, low-iron, at regional storage [RER] (#812)* was used. This inventory includes infrastructure, internal and manufacturing processes such as transportation of raw materials, addition of cullet, melting, forming, cooling, cutting and storage of glass. Tempering of glass (Pressman, 2007) was modelled using the ecoinvent v2.2 process *Tempering, flat glass [RER] (#813)*. It was assumed that the low-iron glass was manufactured in China as Dip coating technology developers use the glass for coating from this country (due to the market price).

2.2.1.2 Transport of uncoated glass

Tempered low-iron glass is packed into wooden boxes. The modelling of packaging is described in detail in Appendix. The boxes with glass are transported from China to the coating plant in the Netherlands by ship. The distance of the transport was assumed to be from the largest Chinese port Shanghai to the port of Rotterdam through Suez Canal. Ecoinvent v2.2 was used for modelling shipment of glass (Appendix).

2.2.1.3 Sol-gel coating production

The coating of glass consists of several steps. First, glass is cleaned, then it is dipped in a sol-gel solution, dried, and then cured. In the cleaning process, the glass is washed with ethanol and deionized water (DI water). The sol-gel solution is prepared with nanoparticles using ethanol as a solvent. After the sol-gel preparation step, the glass is covered with sol-gel (Table 1). The details of production of sol-gel coating can be found in Appendix.

2.2.2 Use of greenhouse glass

2.2.2.1 Packaging and transport of greenhouse glass

The coated glass is packed into wooden boxes, and then transported to the greenhouses by lorry. It was assumed that the end destination was the greenport Westland-Oostland as it is the largest international greenhouse cluster in the Netherlands (Greenport Holland, n.d.).

2.2.2.2 Cleaning of greenhouses

Poot Kasdekreiniging (a company which specializes in the mechanical greenhouse glass washing in the Netherlands (Poot Kasdekreiniging, 2015)), shared details on the cleaning procedure of greenhouses for this LCA study. Poot Kasdekreiniging reported that greenhouse glass should be washed inside once a year and outside twice a year. The amount of water required for the inside cleaning is around 100 L/min (6 m^3/ hour), and the amount of water used for the outside cleaning is around 40 L/min (2.4 m^3 / hour). The machines used for washing the greenhouses were modelled based on data provided by the company Van der Waay (Van der Waay, n.d.). The LCA modelling details of the cleaning of greenhouses can be found in Appendix.

2.2.2.3 Production of tomatoes

The yield of tomatoes produced under coated glass was calculated to be 1692.30 kg/m^2. It was assumed that the greenhouse glass had a functional lifetime in greenhouses for 30 years. Thus, the reference flow for Dip coating was defined as the production of 1692.30 kg of tomatoes in greenhouses under 1 m^2 of Dip coating during 30 years.

2.2.3 Preparation of glass for recycling

Preparation of greenhouse glass for recycling was included in the life cycle model of Dip coating. In this process, the greenhouse glass was collected and transported to the sorting plant where it was sorted, washed, dried and then milled into glass cullet (Blengini et al., 2012). Further transformation of glass cullet into a new product is outside of the system boundary. The details of modelling are given in Appendix.

2.3 Development of what-if scenarios

Scenarios can depict likely futures, possible futures or desirable futures (Quist, 2013). What-if scenarios were developed in the study to simulate the environmental performance of Dip coating at pilot and industrial scales. Three scenarios such as Dip coating at laboratory, pilot, and industrial scales were developed using what-if reasoning as shown in Table 2. In the table all parameters are given per 1 m^2 of glass.

The what-if scenarios used different variables and variable conditions. Contribution analysis of sol-gel production for Dip coating showed that the highest impacts come from electricity production and ethanol manufacturing. Thus, the laboratory parameters related to those processes were determined as the variables: cleaning solution, sol-gel solution, electricity for coating, electricity for curing, and waste. The variable conditions for ‘Dip coating at laboratory scale’ were the values of the electricity amount and volumes of solutions and hazardous waste measured. ‘Dip coating at pilot scale’ and ‘Dip coating at industrial scale’ scenarios were developed by optimizing the variable conditions at laboratory scale.

The electricity required for the work of a dip coating machine at pilot and industrial scales was estimated. The dip coating machine used at laboratory scale has the speeds for the withdrawal of glass from sol-gel of 1, 2, 4, and 8 mm/s. It was assumed that the amount of energy required for the dip coating machine at laboratory scale to dip the glass into the sol-gel solution was negligible. The highest speed of the dip coating machine at laboratory scale, 8 mm/s, was assumed as the work speed both for pilot and industrial scales. It was assumed that dip coating machine for pilot scale was produced to mimic the work of the machine at industrial scale, and therefore, the speed of the glass withdrawal from the coating at pilot and industrial scales was assumed to be equal. The power required for the work of the dip coating machine was estimated using data from the industrial dip coating machine specifications (Alibaba.com, 2017). The work of the dip coating apparatus required 0.56 kWh of electricity to coat 1 m^2 of glass at pilot and industrial scales. According to Sánchez-Cruces et al. (2014), the electricity consumption for curing 1 m^2 glass is 3.33 kWh. This amount of electricity was used for the input of the electricity needed for the curing process at pilot scale. It was assumed that the curing process of the coating was performed in the tempering step at industrial scale. Thus, tempering was modelled as a process which included the curing process using ecoinvent v2.2 in the ‘Dip coating at industrial scale’ scenario.

The masses of cleaning solution, sol-gel solution, and waste were estimated for pilot and industrial scale scenarios. According to Petropoulos et al. (1998), a dip coating machine with a solution displacement apparatus can be used at industrial scale so that the solution could be reduced from 30 to 70%. In this work, it was assumed that there would be a reduction of DI water for glass cleaning, sol-gel solution, and waste by 35% at pilot scale and by 70% at industrial scale.

Table 2. What-if scenarios of Dip coating production. Values correspond to the coating of 1 m^2 of glass

	Cleaning solution	Sol-gel solution	Electricity for coating	Electricity for curing	Waste
Laboratory scale scenario	DI water: 1.00 kg Ethanol: 0.79 kg	0.17 kg	0.00 kWh	8.33 kWh	0.15 kg
Pilot scale scenario	DI water: 0.65 kg Ethanol: 0.00 kg	0.11 kg	0.56 kWh	3.33 kWh	0.10 kg
Industrial scale scenario	DI water: 0.30 kg Ethanol: 0.00 kg	0.05 kg	0.56 kWh	1.11 kWh	0.05 kg

2.4 Sensitivity analysis

Sensitivity analysis of the delayed degradation time and the increased light transmittance of Dip coating was done. The cases when Dip coating started to lose its anti-reflective properties after 20 years and after 30 years rather than after 10 years was analyzed. In the first case, it was assumed that the light transmittance of Dip coating was 96.50% for the first 20 years. After 20 years, the light transmittance of the coating was steadily decreasing each year, so that the light transmittance in the thirtieth year was the same as for Uncoated glass 90.30% (tomato yield was equal to 54.00 kg/m^2). The overall mass of tomatoes grown during the 30 years period was 1710.84 kg/m^2. In the second case, the light transmittance of Dip coating was the same 96.50% for 30 years. The overall mass of tomatoes grown in 30 years was calculated to be 1731.23 kg/m^2.

The effect of the increase of the light transmittance of Dip coating up to 99.00% was examined. It was assumed that after 10 years the coating started to lose its antireflective properties gradually each year. Over 30 years, the mass of tomatoes under Dip coating with 99.00% light transmittance was 1721.45 kg/m^2. Figure 3 shows the yield of tomatoes obtained under Dip coating taking into consideration different degradation times and the light transmittance of 99.00% of the coating. The reference in this figure refers to Dip coating with the light transmittance of 96.50% and the degradation time after 10 years.

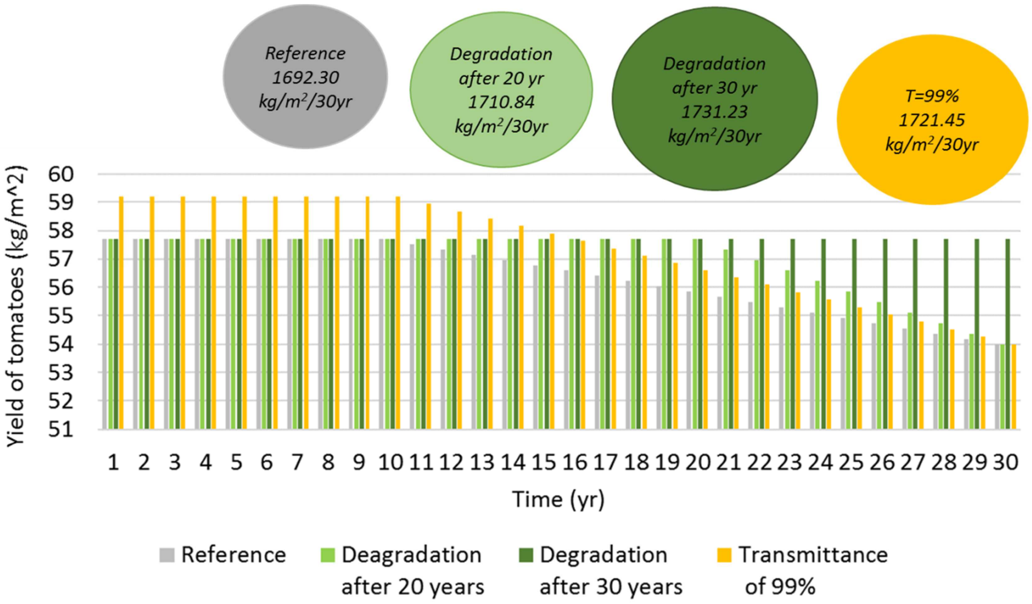

Figure 3. Yield of tomatoes grown under Dip coating with different properties. The bubbles represent the total production of tomatoes under each condition.

Besides performing a sensitivity analysis on the degradation time and the light transmittance, sensitivity analysis also considered modelling alternative locations for the glass manufacturing and coating production. Sensitivity analysis for the locations of the factories were analyzed. Previously, it was assumed that the glass was manufactured in China and then transported the coating plant in the Netherlands. In sensitivity analysis, it was assumed that the glass manufacturing factory was in the Netherlands (the country where the coating plant was located) rather than in China. The option where the coating production plant was in China (the country where the glass manufacturing plant was located) rather than in the Netherlands was also taken into consideration.

The function of the product system was to produce tomatoes in greenhouses during 30 years. The functional unit was defined as the production of 1731.23 kg of tomatoes in greenhouses during 30 years. The details of sensitivity analysis can be found in Appendix.

3. Results

3.1 Comparative analysis results

The conventional greenhouse glass alternatives, which are the references in this LCA study, include Uncoated glass, Acid etching, and Sputtering treated glass. For the novel coatings three scenarios were developed: the laboratory scale production of the new coating (‘lab-scale’), the pilot scale production (‘pilot scale’), and the industrial scale production (‘industrial scale’). In Figure 4, the relative environmental impacts for the references and three novel coating scenarios are compared with respect to the highest result per impact category.

As it can be expected, technologies at laboratory scale tend to have a higher impact than their commercial counterparts and generally much larger impacts than its estimated impacts at pilot and industrial scales. However, results for Dip coating produced at laboratory scale show relatively competitive environmental impacts as compared to the commercial coatings (Figure 4). In acidification and photochemical oxidation, all coatings are within 15% of each other. For the rest of the impact categories, laboratory scale Dip coating is the coating with the highest impact, exceeding its industrial scale impacts by only 10 to 45%. Dip coating appears to be a competitive option due to the fact that its production technique is a simple method which does not require complex equipment. The pilot and industrial scale scenarios for Dip coating show a more promising performance falling within a few percent difference compared to the commercial alternatives of Acid etching and Sputtering.

Despite not requiring a coating process, it was expected that Uncoated glass would have higher impacts compared to the coated glass alternatives due a to lower light transmittance, however results show a competitive environmental performance. This means that coated glass does not bring noticeable advantages in the environmental performance of the greenhouse glass compared to uncoated glass. Instead, it may have the economic benefits from the increased yield of tomatoes (1692.30 kg/m^2/30 yr as opposed to 1620.00 kg/m^2/30 yr). It should be noted that possible indirect environmental benefits were not considered in this study.

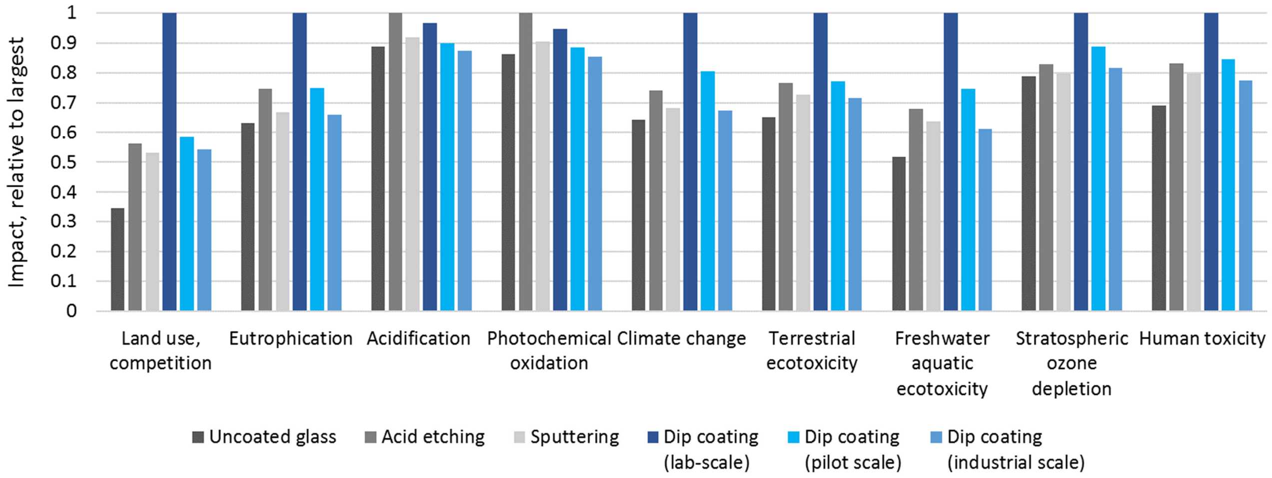

Figure 4. Comparative analysis of the Dip coating production scale scenarios and the references
Note: Results correspond to the functional unit of the production of 1692.30 kg of tomatoes in greenhouses during 30 years.

3.2 Contribution analysis results of the references

Figure 5 shows the breakdown of the processes responsible for the accumulated environmental impact for three references: Uncoated glass, Acid etching, and Sputtering. For all three references and all impact categories the environmental impacts are largely dominated by the low-iron glass production.
The use process is the second main contributor to most of the impact categories, the impacts ranging from 18% to 40% depending on impact categories. In the use phase, transport of greenhouse glass by ship has the highest impacts (See Appendix for details of transport modeling). Land use impact category is related to the contribution of packaging of uncoated and coated glass as the wood from forest is used for the production of the glass packaging boxes. Probably, another packaging alternative could be used for transport of glass instead of wooden boxes. This could result in the reduced impact results in the land use impact category, but on the other hand, this would probably lead to increased impacts in other impact categories. The coating production accounts for a smaller share of impacts (less than 16%) for Acid etching and Sputtering. Glass processing at the end of life contributes the least to all impact categories.

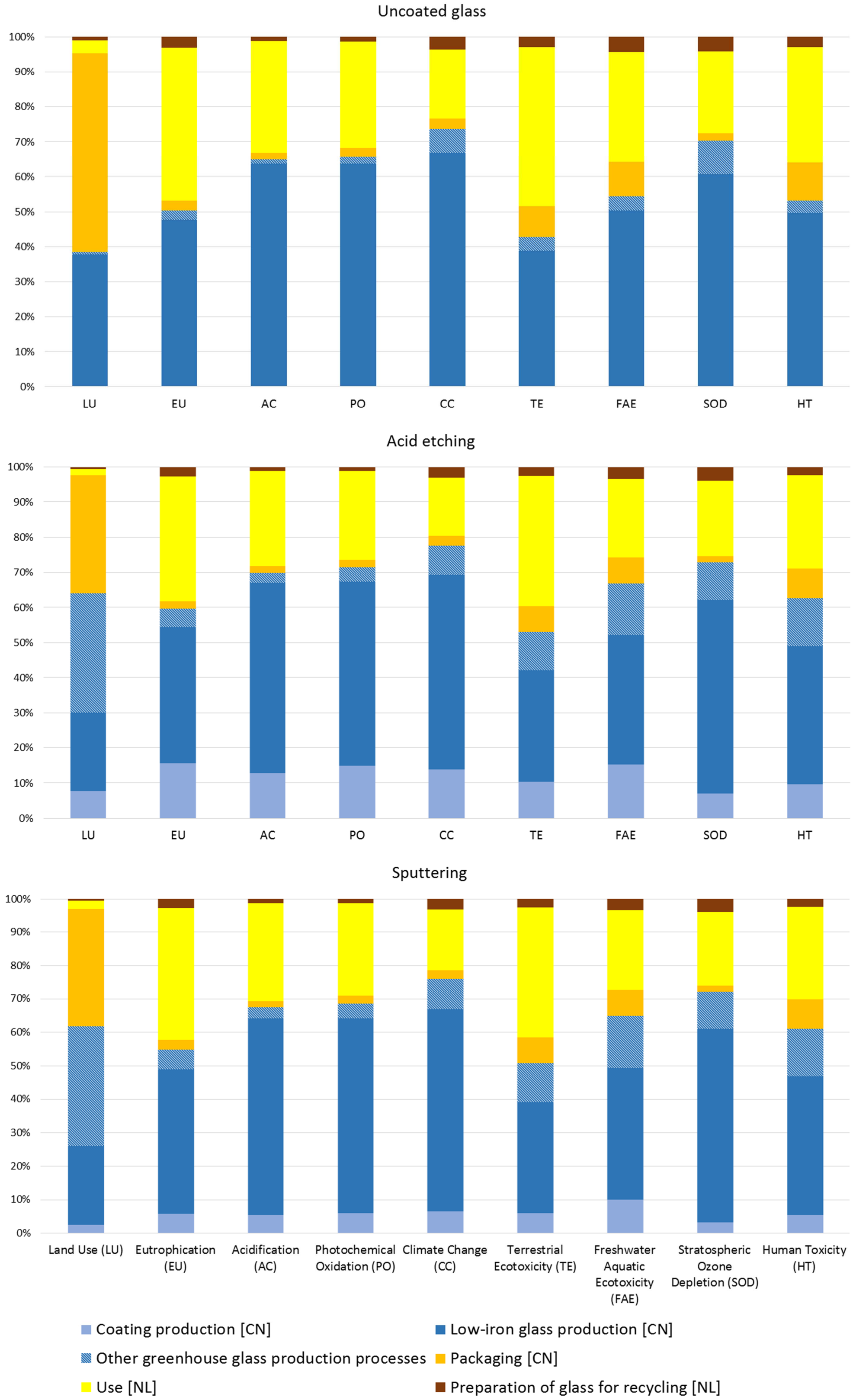

Figure 5. Contribution analysis results of the processes for the references

Further contribution analysis on the coating production for Acid etching and Sputtering (Figure 6) shows that the electricity production is the main contributor to most of the impact categories (up to 72% in Acid etching and up to 79% in Sputtering) followed by fluosilicic acid for Acid etching (the main coating element) and by transport of goods for Sputtering (transport by lorries, trains, and cars).

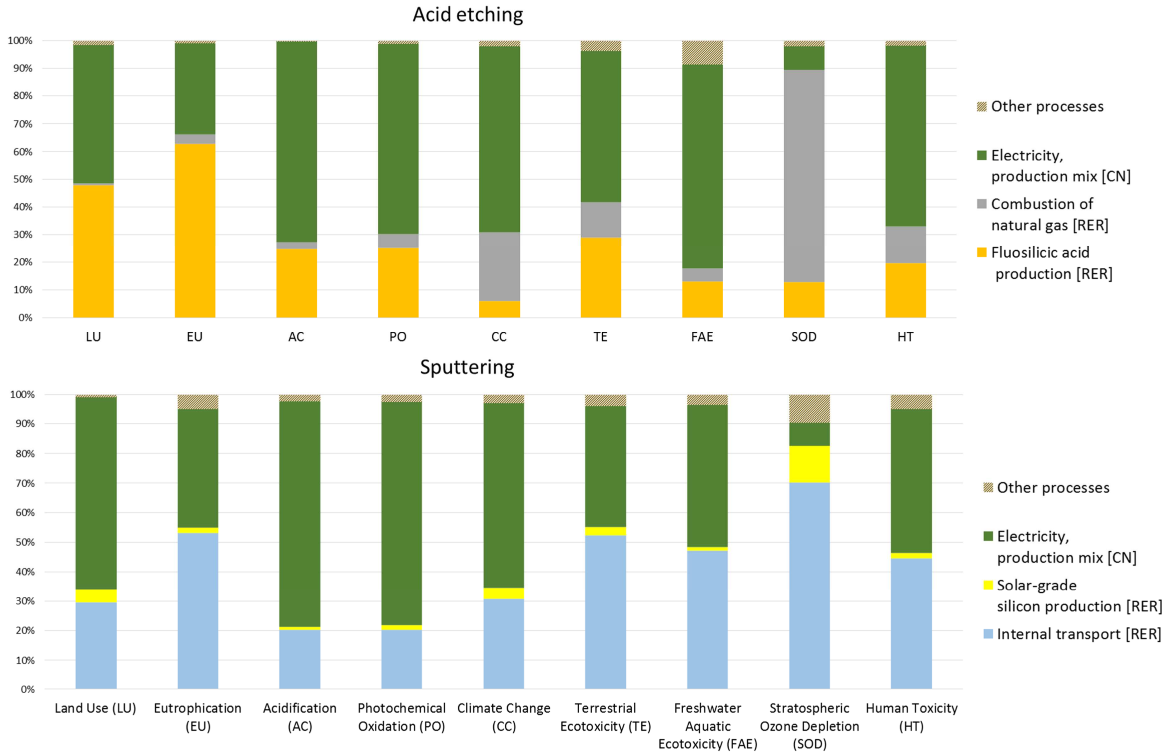

Figure 6. Contribution analysis results of coating production process for Acid etching and Sputtering

3.3 Contribution analysis results of Dip coating

Figure 7 depicts contribution analysis results of Dip coating at different scales. The low-iron glass production has the highest impacts in most of the impact categories. Land use is mainly dominated by packaging. Transport of glass by ship from China to the Netherlands shows contributions between 1% in land use and 30% in acidification. The use phase has a higher share of impacts in terrestrial ecotoxicity compared to other impact categories, and this is mainly due to the release of chromium to agricultural soil from the treatment of sewage in waste water treatment (Appendix). At laboratory scale, the production of ethanol used in the sol-gel preparation has the highest contributions to land use (48%) compared to other impact categories. The high contribution to land use is due to the use of sweet sorghum for the ethanol production. The electricity production mix used in the sol-gel preparation has the highest contributions to climate change (28%) at laboratory scale. This is due to the emissions of carbon dioxide to air from burning natural gas in the power plant. Furthermore, the results show that as Dip coating goes from laboratory scale to industrial scale, the share of impacts coming from the sol-gel preparation (shown in Figure 7 as the electricity production, the ethanol manufacturing, and other processes in sol-gel preparation) decreases gradually – this is due to the economies of scale that come with scale-up.

Preparation of glass for recycling has a small share of impacts ranging in 1-3% at laboratory, pilot and industrial scales.

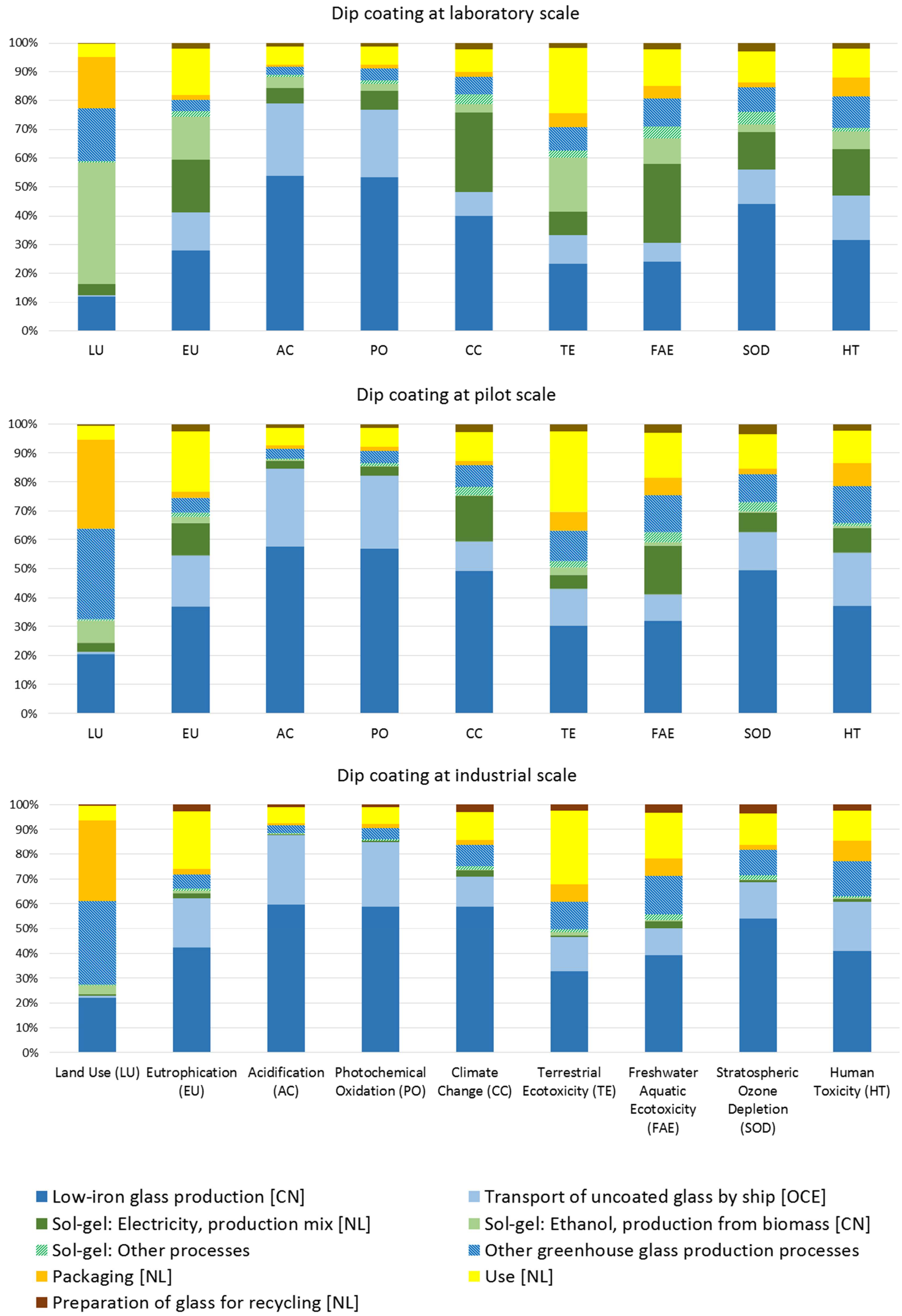

Figure 7. Contribution analysis results for Dip coating scenarios

3.4 Sensitivity analysis results

Sensitivity analysis for 'Dip coating at industrial scale' scenario was performed to explore which technological development option could result in the improved environmental performance of Dip coating in the future (Figure 8). Reference in this case refers to 'Dip coating at industrial scale' scenario, where Dip coating has a light transmittance of 96.5% which starts to degrade after 10 years, glass is manufactured in China, and the coating process takes place in the Netherlands. Five variations of this default industrial scale scenario for Dip coating were tested to evaluate the effect of delayed degradation time, improved transmittance, glass and coating manufacturing locations on the results (Figure 8). Details of the technological development options are described in section 2.4 Sensitivity analysis and Appendix.

The sensitivity analysis results show that most variations to the reference industrial scale scenario, do not have a significant influence in the outcome of results with a difference falling between 10% across impact categories. This is the case for improved performance parameters such as light transmittance and degradation time. From the factors evaluated, the location of glass production (more specifically, the energy mix and decreased distance for the transportation of uncoated glass between the glass manufacturing factory and the coating plant) holds the most promise for improvement of the technology. Locating the plant in the Netherlands instead of China, where the electricity grid derives from coal for the most part and reducing the distance of the transportation of the glass, could decrease the industrial scale impacts of Dip coating by close to 40% in acidification and photochemical oxidation, and by close to 20% in climate change, terrestrial ecotoxicity, freshwater aquatic ecotoxicity and human toxicity.

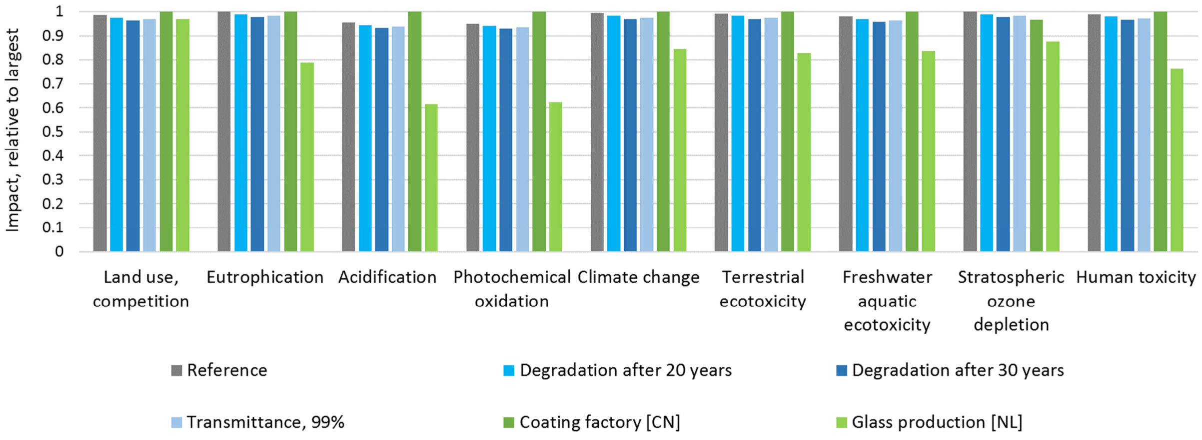

Figure 8. Sensitivity analysis results for Dip coating at the industrial scale scenario. The reference refers to the default Dip coating system at industrial scale. Variations of this are labeled according to the changed parameters. For instance, "degradation after 20 years" refers to the same Dip coating product system as shown in Figure 4, but with a coating degradation after 20 years instead of 10 years. Results correspond to the functional unit of the production of 1731.23 kg of tomatoes in greenhouses during 30 years.

4. Discussion

Anticipatory LCA with the aid of what-if scenarios was used to guide R&D of the coating innovation technology towards improved environmental performance. Some findings could be highlighted in this research. First, given the lower transmittance of Uncoated glass, it was expected that Uncoated glass would have greater impact results than other alternatives. However, without the additional burdens of the coating production, Uncoated glass is an environmentally competitive alternative. Nevertheless, Acid etching, Sputtering, and Dip coating bring economic benefits in terms of increased yield of tomatoes due to the fact that the same amount of tomatoes can be produced under coated glass in a shorter period of time but do not bring significant benefits in terms of the environmental performance to greenhouse glass. Another finding is that a simple coating method, dip coating, which does not require complex equipment than sputtering, has the potential to become an environmentally advantageous alternative.

The study revealed that 'Dip coating at industrial scale' scenario could have approximately the same impact results as conventional coatings such as Acid etching and Sputtering in the future. It would be recommended to use glass manufacturing in the Netherlands rather than in China since this would result in the best environmental performance for Dip coating due to the national energy mix and decreased transportation distance (Figure 8). The electricity produced in China is mostly from hard coal (79%), whereas the electricity produced in the Netherlands is mostly from natural gas (62%). Light transmittance and degradation time, two key performance parameters which are the focus in innovation for coating technology, did not have such a strong influence in the impact results as expected in the beginning of the research. The energy mix of glass manufacturing has to be evaluated taking into account the transport of glass. Ideally, glass manufacturing uses green energy and is close to the point of use. With regards to the energy mix in glass manufacturing, it is important to consider the future improvements in national grid mixes, which will affect the environmental impact of glass.

It could be expected that the environmental impacts of glass manufacturing in China would be significantly lowered by 2040 provided improvements to the energy mix. According to EIA (2017), the coal-fired electricity production in China will decrease from 72% in 2015 to 47% in 2040 and the renewable share of total production in China will increase from 22% in 2015 to 34% in 2040. The share of nuclear production will rise from 3% in 2015 to 11% in 2040, and the natural gas share will increase from 2% in 2015 to 7% in 2040. At the same time, glass manufacturing in the Netherlands would also have lower environmental impacts compared to the measured impacts in this LCA study. EIA (2017) reported that in OECD, the electricity generation mix will change significantly by 2040 with nuclear power and liquid fuels declining, coal remaining flat, and renewables and natural gas growing.

In addition, some limitations of this study could be determined. First is that data on the environmental extensions (biosphere inputs and emissions) for the Dip coating production was unavailable. To this end, a sensitivity analysis (Appendix) was performed to find out if the environmental extensions for the coating production of the reference coatings influence the overall results of the coatings product systems. It was revealed that the environmental extensions for the production of the coating contribute a negligible share of the impacts, and thus it can be assumed that environmental extensions data for Dip coating production will not play an important role in the environmental performance.

Another limitation exists with regards to the selected variables and variable conditions in the what-if scenarios. Variables were based on expert knowledge and given the number of variables it is possible that this study misses other important variables that could be identified by further stakeholder and expert engagement. Further iterations of the anticipatory LCA approach applied in this study could make use of stakeholder analysis to map the relevant stakeholders. This assessment would help to view their level of interest and influence in the project and broaden the decision-making process. The identified stakeholders could be asked for the participation in the construction of what-if scenarios including social aspects which would broaden the view of the assessment. Another way to develop the methodology further is to move to more advanced types of scenario development. Whereas what-if scenarios are rather simple, yet very useful ways of creating diversity in possible end-states and to distinguish between R&D phase, pilot phase and full production, there are scenarios methodologies that allow for considering greater diversity, more uncertainties, and also varying economic and social contexts, such as General Morphological Analysis (Baran, 2016) and backcasting (Quist, 2013).

5. Conclusion

The study recommends the use of anticipatory LCA for the assessment of innovations early in R&D stages. In this work, anticipatory LCA was used to guide the coating technology towards improved environmental performance. What-if scenarios were applied in conjunction with anticipatory LCA to scale-up the coating technology system from laboratory to pilot and industrial scales.

Several findings were made in this work. The new coating would be competitive with the conventional coatings in terms of the environmental performance at industrial scale in the future. This could be due to the simplicity of the coating production method of the novel coating.

The functional unit representing the area of the greenhouse glass per m^2 reflects the difference in the performance of the coating. However, in this study, the production yield of the crop is included in the functional unit as this makes it possible to assess the coatings taking into consideration the economic benefits of coated glass over uncoated glass. It was revealed that the benefits of coatings are not necessarily reflected in the environmental performance but in the production yields of tomatoes. Sensitivity analysis showed that the change of the location for the glass manufacturing can significantly affect the impact results of the product system of the new coating.

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7. Appendix

Supplementary data for this article can be found in Appendix.

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