Managing Glass Waste in Energy Efficient Building Retrofitting: Barriers and Opportunities for a Circular Economy

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Abstract. Making cities resilient and sustainable is only possible if the energy consumption of buildings is reduced. Retrofitting is one of the main tools of the environmental policies developed in cold and temperate climates, leading to the replacement of products considered inefficient. This is particularly the case for glazing, which is a key element in the energy system of a building. However, most of the glass waste generated by renovation is landfilled while the development of a circular economy in the glass industry seems today highly challenging. This paper studies barriers and opportunities to increase the recycling and repair of insulating glass units. To do so, we follow three approaches: a literature review, a series of interviews and a case study of a glazed office district in Brussels. This article provides a comprehensive overview of the main issues relating to the management of glass waste in the building sector and underlines the importance of economic instruments to support the spread of sorting and recycling practices. The need to rethink the systems for assembling insulating glass units with a view to facilitating the sorting of their components also appears as a necessary and stimulating path.

1. Introduction
The building sector is one of the largest contributors to global warming partly due to the incredible amount of energy consumed maintaining indoor climates at a certain level of comfort [1]. Therefore, since the 1970s, one of the priorities of environmental policies has been to optimise the energy performance of buildings [2]. This is mainly achieved through better insulation, which improves the thermal resistance of the façade.

Compared to the performance of an opaque wall, windows are a point of weakness in a building’s insulation. The air permeability of their assembly, as well as the thermal conductivity and transparency of the glazing, result in considerable passive solar gains and heat losses, undergone or controlled throughout a design process highly dependent on weather and climate. As a result, thermal regulations have required the building industry to invest in the research and development of ever more efficient products.

However, by focusing almost exclusively on energy consumption at the expense of other ecological impacts and on the use phase at the expense of the other stages in the life cycle of buildings, this policy has overshadowed important ecological issues. Indeed, insulating glass units (IGU) are never repaired and almost never recycled. Thus, the replacement of a glazing results de facto in the production of a waste which is usually landfilled [3]. The environmental cost of such a practice is incompatible with the sustainable development goals as defined by the United Nations, especially regarding the need to ensure
sustainable consumption and production patterns [4]. Thereby, at a time when many countries around the world intend to strengthen their thermal retrofit policies—and thus foster the replacement of IGUs regarded as inefficient—the following questions must be urgently addressed: What are the obstacles in the industrial processes that prevent the recycling of glazing? To what extent does the design of an IGU affects its recyclability? What are the possible paths of development?

To answer these questions, we reviewed professional journals published since 1970 to analyse how the management of building glass waste has been addressed and whether any initiatives have already been implemented. The information gathered was supplemented by interviews with the main stakeholders from the glass waste sector within the Brussels-Capital Region. Through this process, we have been able to identify and discuss recent developments as well as challenges faced by the industry when implementing solutions to reduce the amount of landfilled IGUs. Finally, we made use of this knowledge by focusing on a case study: the glazed office towers in the northern district of Brussels. Through an analysis of the material flows generated by the production and replacement of the curtain walls of these buildings, we study different scenarios of evolution and discuss their ecological impact.

Throughout this research, we have focused on the glass industry in North-Western Europe and, although the case study is centred on Brussels, the findings can be applied to other regions. Indeed, the production processes as well as the constructive systems (insulating glass units and curtain walls) are similar to those used in many countries around the world which are also facing issues of architectural glass waste in the retrofitting of energy-intensive, fully glazed buildings. Hence, the results of this study provide useful knowledge toward the development of sustainable consumption and production patterns for glazing in many countries around the world.

The next section presents the methodology which relies on three complementary approaches: a review of the literature published since the 1970s (section 2.1), interviews of stakeholders (2.2) and a prospective material and energy flow analysis of the glazed offices in the northern district of Brussels (2.3). The third section presents the results in four successive steps: an overview of the European situation is given (3.1); the reasons why glazing is most often landfilled are then discussed (3.2); a range of solutions applicable at different stages of the life cycle of glazing is analysed (3.3); and the main results of the case study are outlined (3.4). Finally, the fourth section discusses the paths which must be taken to support the development of an economy which would no longer operate on a linear but on a circular model, with the aim of making cities and human settlements resilient and sustainable (UNSDG11) while ensuring sustainable consumption and production patterns (UNSDG12).

2. Methodology

2.1. The literature review

The first stage of this research consists of reviewing professional journals and reports published since the 1970s in Western Europe. The objective of this review is threefold: to understand how the recycling, repair and reuse sectors are structured; to reveal the obstacles constraining the development of these sectors; and to identify initiatives aimed at removing these obstacles.

To do this, we review four of the leading trade journals—Glass Magazine, Glass Technology, Verre, and Glaces et verres—as well as 18 reports¹ published since 1974. This date is the year when the first thermal regulations were introduced in many European countries², accelerating the diffusion of IGUs. The management of IGUs at the end of their life cycle emerged as early as the 1980s as an important issue and our historical research approach provides a comprehensive understanding of the initiatives and constraints that have shaped the socioeconomic metabolism of the glass industry and its waste streams.

¹ These reports were selected on the basis of a keyword search (flat glass, recycling, reuse and repair) on the websites of national environmental agencies (e.g., the Environmental Agency in UK, the ADEME in France) as well as on the search engine of the Université libre de Bruxelles.
² Such as the RT74 in France or the BSN534 standard in Belgium. However, the diffusion of IGUs will not happen at the same speed: e.g., while double glazing became common in Germany in the 1980s, this product had to wait for the RT2000 to be widely used in France.
2.2. Interview of stakeholders
The literature review is enhanced by a field survey conducted through a series of semi-structured interviews with two of the main glass industries, two companies specialised in glass waste management, and two deconstruction firms. Based in the heart of the European glass industrial region, these companies are key stakeholders in the current market related to the processing of glass waste coming from buildings.

The purpose of these interviews is twofold: to understand the barriers—economic, technical, legislative—of recycling and reuse practices; and to identify ongoing research and development aiming to reduce the landfilling of IGUs. This survey, therefore, provides an overview of possible future scenarios, while the literature review reveals past actions undertaken in the hope of reducing glass waste production.

2.3. Analysis of glazing flows: a case study
The last stage of our research consists of a material flow analysis (MFA). The objective is to assess incoming and leaving flows as well as stocks of glazing involved in the maintenance, transformation and destruction of a certain building stock over a long time period.

To do so, we conduct an MFA through a specific case study: the fully glazed office buildings in the Northern Quarter of the Brussels-Capital Region. This building typology has been chosen because of the architectural and ecological challenge that the thermal retrofitting of the facade of these energy-intensive edifices represents. Such a challenge concerns almost every country in the world given the wide diffusion of this typology which is mainly composed of a curtain wall most often poorly designed to local climatic conditions.

In this business district, the first curtain wall was designed for the Martini tower, built between 1957 and 1960. Since then, construction and deconstruction have followed one another at a steady pace to reach a total of eighteen buildings standing with curtain walls today. Three of which are undergoing major renovation with the replacement of glazing while three new fully glazed towers are under construction.

Accordingly, a retrospective analysis of the glazing flows entering and leaving this scope of study has been carried out from 1960 to the present day, also taking into account ongoing construction and renovations expected to be completed by 2025. In addition, based on this inventory, the stock of glazing currently in use is analysed according to four scenarios of evolution depending on retrofitting and waste management strategies: existing IGUs are replaced (a) by solar control double glazing or (b) by three

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3. This research only considers glazing, thus frames are not included.
4. This building was demolished in 2001-2002.
layers of glass consisting of triple glazing or double-skin facade\(^5\); these two scenarios are combined with
those defining the recycling rate of the replaced glazing as (c) a business-as-usual baseline (a rate of
5\%) or (d) an optimistic outlook (a 50\% rate).

An important assumption for this prospective analysis is the service life of the facades, which is
assumed to be 40 years. This period is calculated on the basis of observations made on eight buildings
that have already been renovated or destroyed in the North Quarter since 1960: the average lifespan is
42 years, rounded down to 40 years\(^6\).

Finally, along with the MFA, the global warming potential (GWP) resulting from the production,
transport and recycling of glazing is assessed. This assessment relies on environmental product
declarations (EPDs) published by the firm AGC in 2019 [5]. These declarations concern double and
triple glazing and provide data on greenhouse gas (GHG) emissions during their production, transport
and end-of-life phases. The end-of-life scenario used in these EPDs considers the current recycling rate
which is close to zero. In the modelling of the scenario with a 50\% recycling rate from 2025 onwards,
the following assumptions are made: for each ton of cullet, raw material consumption is reduced by
1.2 tons [6] and CO\(_2\) emissions are cut by 300 kg [7]. A final assumption relates to the transport of the
used glazing which is done by truck over an average distance of 100 km from the building site to the
treatment centre, and over a distance of 50 km from the treatment centre to the glass manufacturer.

3. Results
The results are presented in three sections. Firstly, we summarise the data collected on waste flows of
architectural flat glass in Europe. Secondly, we discuss the barriers preventing the diffusion of recycling
and reuse practices. Finally, we share the results of the MFA focused on the Northern Quarter of
Brussels.

3.1. Glass flows across Europe
In 2018, about 8 million tons of architectural flat glass were produced in the European Union [8,9]. The
glass industry has thus exceeded its pre-crisis production rate, which was estimated to be between 5.6
and 6.5 million tons in 2008 [10].

The manufacturing of glazing is the first source of glass waste. This waste results mainly from offcuts
with a composition and purity easily controllable under the cleanliness conditions of the production and
transformation plants. As a result, 95\% of these offcuts are crushed and recycled directly within float
glass furnaces [11]. According to Glass for Europe, in the EU-28, between 750,000 and 1 million tons
of offcuts are generated each year, corresponding to 10-15\% of the production.

In contrast, although glass is an inert material that can theoretically be recycled endlessly, used
glazing from renovation and deconstruction sites is almost never recycled [3,7,11,12]. Instead, this waste
is most often crushed and landfilled. To a lesser extent, it can be downcycled as granulates or as raw
material for the production of glass containers and glass wool. In 2013 in the EU-28, glass waste from
the building sector represented a flow of approximately 1.5 million tons coming from renovation (83\%)
and deconstruction (17\%) of tertiary (42\%) and residential (58\%) edifices [3]. In 2005, this flow
represented around 1.2 Mt/year in the then 25 member-state Europe [10].

These glass waste flows within Europe are illustrated in figures 2 and 3. The first one shows the
trajectories of pre-consumer cullet, while the second one presents the flows of post-consumer cullet.

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\(^5\) The double-skin facade consists of a double glazing on the inside and a single glass on the outside. This system
is in use in a few towers of the district. Glass masses vary from 35 to 40 kg/m\(^2\) for double glazing, and from 55
to 60 kg/m\(^2\) for triple glazing and double-skin facades, depending on building design.

\(^6\) Lifespans range from 40 to 48 years. The buildings that have not yet been renovated were all constructed less
than 30 years ago.

\(^7\) Direct CO\(_2\) emissions from glass melting are cut by 200 kg-CO\(_2\) per ton of cullet while indirect CO\(_2\) emissions
from fuel consumption are reduced by approximately 100 kg-CO\(_2\) per ton of cullet. The use of 50\% of cullet in
glass furnaces reduces the fuel consumption from 12.5\% to 15\% [3].
3.2. Why is it complicated to avoid landfilling glazing?

3.2.1. Barriers to repair and reuse. The first action to avoid glass waste generation would be to repair and reuse glazing that is considered defective or not efficient enough. This would be particularly useful in the event of condensation appearing within the inner cavity of IGUs, a frequent problem when the assembly is no longer hermetic and which de facto reduces energy performance and transparency.

Nevertheless, an insulating glass unit is considered almost irreparable. Indeed, the gasket that bonds the two or three sheets of glass and guarantees the tightness of the inner cavity is so strong that it is impossible to safely\(^8\) separate the components in order to access the cavity to clean and repair it. Moreover, the widespread use of heat-toughened glass prevents the cutting or drilling of glass sheets.

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\(^8\) Especially since the fragile and sharp character of glass makes the repair unsafe.
As a result, while window repair practices were common until the advent of insulating glass, they are now marginal, with glazing and frames most often ending their life cycles in landfills.

3.2.2. Barriers to recycling. Glass recycling has many advantages. Once crushed, the cullet goes back into the furnace and saves a large quantity of resources—1.2 tons of raw materials per ton of cullet, including nearly 700 kg of sand—and facilitates the combustion of the glass batch, resulting in a reduction of GHG emissions by some 300 kg per ton of cullet.

However, while almost all offcuts from production and transformation plants are recycled, post-consumer cullet coming from renovation and demolition sites is hardly ever recycled. This is due to the great difficulty experienced by the glass recyclers in guaranteeing the cullet quality required by the flat glass industry. “Standards for flat glass in buildings give a maximum number of three < 1 mm faults per jumbo pane (3 m per 6 m). This is the equivalent of three pound coin sized faults on a football pitch” [13]. Indeed, contaminants can lead to production losses over several days and cause serious damage to the furnace while the sorting represents a challenge for the treatment centre9: for example, small particles of glass ceramics and borosilicate glass are very difficult to detect due to their transparency.

3.3. What alternatives to landfill?

3.3.1. Repair and reuse practices. The limited durability of IGUs, caused mainly by the wear of gaskets and a resulting condensation in the inner cavity, was an early concern for some engineers who wished to provide solutions for the cleaning and repair of these units. At the end of the 1980s, their research led them to register patents of repair techniques for defective glazing [14, 15]. These patents consist of desiccant materials filled in small boxes which are plugged on the inner surface of the interior glass pane at a point where a hole has previously been drilled10.

Nevertheless, the impact of these techniques on the transparency of the glazing and the complexity of the process compared to the cost of a new product have limited the development of these boxes. Accordingly, repair practices persist only in some renovation projects where the windows have a significant heritage value. In such context, the use of secondary glazing or double windows allows for the existing single glass pane as well as the original frame to be maintained [16–18]. However, it is important to point out how marginal these practices remain.

3.3.2. Solutions to recycle. The increase of the recycling rate of IGUs coming from renovation and demolition sites today is mainly based on the development of high-performance technologies for separating glass and contaminants along a complex sorting process. This requires a heavy investment that increases the price of cullet and reduces its competitiveness even though raw materials are comparatively cheap and landfilling costs relatively low in most European countries. Thus, the development of these technologies is not sufficient to extend the recycling of post-consumer flat glass, and, moreover, does not solve the problems related to the recycling of spacers and gaskets.

In response, economic instruments (taxes and financial incentives) appear to be essential and have proven effective in countries that have succeeded in increasing recycling rates [19]. In addition, the development of new glazing with a design that facilitates their recycling is an attractive solution. This is the path followed by AGC, for example, in the development of vacuum glazing made of materials that can all be recycled directly in glass furnaces11.

9 “Any contamination of the recycled glass used to manufacture flat glass will cause rejectable defects. Once introduced into a furnace contamination can take several days to pass through the system. Thus low levels of contamination can result in several days of lost production which will cancel out the environmental and cost benefits of recycling.” [13]

10 The increasingly widespread use of toughened glass prevents the cutting or piercing of the glazing, which would break into a thousand pieces due to internal stresses.

11 A very small amount of ceramic welded to the glass panes acts as the spacer and sealant, and can be directly recycled in flat glass furnaces. See: AGC Glass Europe, <www.fineoglass.eu>, accessed 10 April 2020.
3.4. Building stock and glazing flows: a case study.
This section presents the results of the MFA which focuses on glazing used in the curtain walls in the North Quarter of Brussels. Through a retrospective approach described previously (2.3), we assess the flow of glazing entering and leaving the area of study and estimate the resulting stock of IGUs currently in use. Finally, the environmental issues related to glazing retrofits is studied through an estimation of the GWP according to four scenarios listed in the table 1.

| Scenario 1 | Existing glazing replaced with solar control double glazing |
|------------|-------------------------------------------------------------|
|            | 1a. Current recycling rate | 1b. Recycling rate of 50% |
| Scenario 2 | Existing glazing replaced with triple glazing or double-skin facade |
|            | 2a. Current recycling rate | 2b. Recycling rate of 50% |

Figure 4 shows the evolution of glass flows since 1950. In the first graph, we can observe a continuous growth in the incoming flow to today. This is mainly due to the construction of new buildings, while only one renovation took place in 2004. However, the importation of new glazing is very likely to be increasingly driven by the renovation of an ageing building stock, as illustrated by the current situation: three towers are under construction and three others are under renovation.

Accordingly, the leaving flow of glass until today has resulted mainly from building destruction (except in 2004 during the first renovation of a curtain wall). In the decades to come, however, the production of glass waste is expected to be mainly generated by renovation work, while the glazing stock should remain rather stable unless façade retrofits involve three layers of glass.

Figure 5 shows the assessment of the global warming potential of the four scenarios under consideration. The replacement of existing glazing with triple glazing or double-skin facades leads to a considerable increase in GHG emissions that an optimistic recycling rate (50%) cannot compensate for. Indeed, the GHG emissions related to the transport of glass waste, its treatment and finally the production of new glazing remain very high in comparison to the volume of GHG emissions potentially avoided. Finally, it is clear from this graph that the solution to limiting the global warming potential relating to the consumption of glazing is to reduce the amount of glass produced.
Figure 4. Evolution of glazing flows (input, output and resulting stock) in the Northern Quarter of Brussels, in thousands of tons.

Figure 5. Global warming potential resulting from the consumption of glazing over the next decades according to recycling rates.
4. Discussion
This research underlines the value of a life cycle approach to environmental issues related to the building sector. However, this analysis is essentially based on an MFA that does not take into account greenhouse gas emitted during the use phase of an edifice. This stage is of crucial importance and the potential energy savings resulting from more efficient glazing is an important marketing argument today. This research should therefore be further developed through a life cycle assessment including this step.

Nevertheless, this study brings to light the challenges related to the management of building stock, with maintenance and renovation constituting an important barrier to the development of a circular economy. The increasing complexity of glazing (in particular through the use of triple glazing and double-skin façades) not only contributes to the growth of the material stock, but also makes it increasingly difficult to improve the recycling rate.

While the warranty period for glazing does not exceed 30 years and the service life of curtain walls ranges between 40 and 50 years, repair practices could be an effective solution to lower the environmental footprint of the building sector. To this end, the research and patents developed in the 1980s to address the problem of condensation in the interior cavity should be studied and revisited.

5. Conclusions
This research highlights the urgency of developing innovative technologies to extend the service life of glazing through the implementation of techniques which allow for the reuse and ease of recycling IGUs. Moreover, the growth of the glazing stock should lead western European regions to address urgently the issues relating to the management of ageing construction products beyond recyclability. This is an issue of great importance for the future of our cities and the biosphere.

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