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Decarbonizing the glass industry: A critical and systematic review of developments, sociotechnical systems and policy options

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Abstract: Glass is a material inextricably linked with human civilization. It is also the product of an energy intensive industry. About 75% to 85% of the total energy requirements to produce glass occur when the raw materials are heated in a furnace to more than 1500 °C. During this process, large volumes of emissions arise. The container and flat glass industries, which combined account for 80% of total glass production, emit over 60 million tonne of CO_2 per year. However, environmental issues relating to the glass industry are not just limited to the manufacturing stage, but also from raw materials extraction, which impacts local ecosystems and creates other environmental challenges associated with tailing ponds, waste disposal and landfills. This systematic review poses five questions to examine these issues and themes: What alternatives exist to abate the climate effects of glass and thus make the full life cycle of glass more sustainable? What are the key determinants of energy and carbon from glass? What technical innovations have been identified to make glass manufacturing low to zero carbon? What benefits will amass from more carbon-friendly process in glass manufacturing, and what barriers will need tackling? To examine these questions, this study presents the findings of a comprehensive and critical systematic review of 701 studies (and a shorter sample of 375 studies examined in depth). A sociotechnical lens is used to assess glass manufacturing and use across multiple sectors (including buildings, automotive manufacturing, construction, electronics, and renewable energy), and options to decarbonize. The study identifies a number of barriers ranging from financial to infrastructural capacity, along with high potential avenues for future research.

Keywords: climate change; climate mitigation; glass; industrial decarbonization; net-zero; energy policy; glass manufacturing; glass processes; sustainability transitions; innovation

Acronyms and Abbreviations

Al_2O_3	Aluminium oxide
B_2O_3	Boron oxide
BaO	Barium oxide

BAT	Best Available Technology
BECCS	Bio-energy with carbon capture and storage
BEIS	Department for Business, Energy & Industrial Strategy
BIPV	Building-integrated photovoltaics
c-Si	Crystalline silicon
CaO	Calcium oxide
CRT	Cathode-ray tubes
CCS	Carbon capture and storage
CCUS	Carbon capture utilisation and storage
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CCUS	Carbon capture, utilisation and storage
EPR	Extended Producer Responsibility
EV	Electric vehicle
EC	Electrochromic
EoL	End of Life
EU	European Union
EU-ETS	European Union Emissions Trade Scheme
GFRP	Glass fibre-reinforced plastics
GHG	Greenhouse gas
GW	Glass waste
GWP	Global warming potential
HBO_2	Metaboric acid
IEA	International Organization Agency
IRENA	The International Renewable Energy Agency
ITI	High Temperature Insulation
K_2O	Potassium oxide
LCA	Life-cycle assessment
LCD	Liquid-crystal display
MgO	Magnesium oxide
MTOe	Million Tonnes of Oil Equivalent
MSW	Municipal Solid Waste
Na_2O	Sodium oxide
NOx	Nitric oxide
ORC	Organic Rankine cycle
PbO	Lead oxide
PCB	Printed circuit boards
PET	Polyethylene terephthalate
PV	Photovoltaic
RD&D	Research, Development & Deployment
SAT	State-of-the-art
SCC	Self-compacting concrete
SG–PBS	Grass polybutylene succinate
SiO_2	Silicon dioxide
USD	United States dollar
UK	United Kingdom
UN	United Nations
US	United States
WGS	Waste glass sludge

Units

cm	centimetre
G	gram
GJ	Gigajoule
GW	Gigawatt
GWh	Gigawatt hours
kg	kilogram
kt	kiloton
kW	kilowatt
MJ/kg	Megajoules per kilogram
Mm	millimetre
MWh	Megawatt-hour
MW	Megawatt
PJ	Petajoule

1. Introduction

Glass is a vital material for society and modern technologies. However, it is often overlooked and forgotten[1]. Glass is a fragile, transparent yet impermeable, nontoxic, inert and a non-crystalline material[2]. It is omnipresent in our society, present in the screens of our mobile phones, televisions and computers. it is in our cars, in drinking containers; and the glasses that help us read. Glass is also present in less visible applications, such as fiberglass for insulation and reinforcement, fibre optic cables for telecommunications, waste glass for construction materials and nuclear waste encapsulation[3]. Other applications for glass include biomedical devices and implants in medicine (e.g. keyhole surgery) and dentistry, electrophotography, electronic switches and memories, lasers, solder and sol-gel glass, sensors and non-linear, active and digital optics[4].

More recently, glass has also become instrumental in many low-carbon innovations. It has played a pivotal role in the development of high capacity batteries, data storage and 3-D printing[5]. Glass is also a crucial element in the environmental-design arena,[3] not only by increasing the energy efficiency of buildings[6] but also as being a key material in the composition of solar panels [7] and wind turbines[8]. Given the ubiquity of glass, it is not surprising that global production of glass was close to 130 million tons in 2020[1]. As **Figure 1** indicates, the production of glass and its relation to society has a long history— it has been produced for thousands of years, with the oldest glass findings dating from as early as 3500 BC[9]. Thought to be initially originated in Egypt, it was later independently developed in China, Greece and Northern Tyrol[10]. Around 1500 BC, the production of glass significantly increased, when larger and more utilitarian objects (e.g. containers, cups and bowls) were built by moulding glass around a sand or clay core[11]. Key glass revolutions took place in the 1st Century AD in Syria, with the development of the glass blowing pipe and later, in the 8th to 9th Century when glassmaking in the Levant reverted to plant-ash based recipes[9] [12]. These techniques permitted the production of a variety of glass shapes and let to the introduction of glass to the western world. The evolution of glass continued, in 1688, under Louis XIV's reign, when large surface mirrors were developed for the Palais Versailles[11] and later, in the 14th Century, when Venice became the European Centre for glass art at Murano, followed by Czech glass (e.g. Swarovski) and Waterford glass in Ireland. Fast forwarding to the 19th Century, the ground-breaking invention of the regenerative furnace by Sir Karl Wilhelm Siemens, allowed large-scale continuous production of glass and the use of machinery[13]. Later, in the 20th Century, two important events took place. First, the full mechanisation of the automatic bottle manufacturing process in the 1920s[11] and Alastair Pilkington's invention of the float process for flat glass in 1952[14]. These two developments paved the way for the production of an individual section machine to be above 500 bottles per minute, and the production of float glass to be up to 1000 tonnes/day[11].

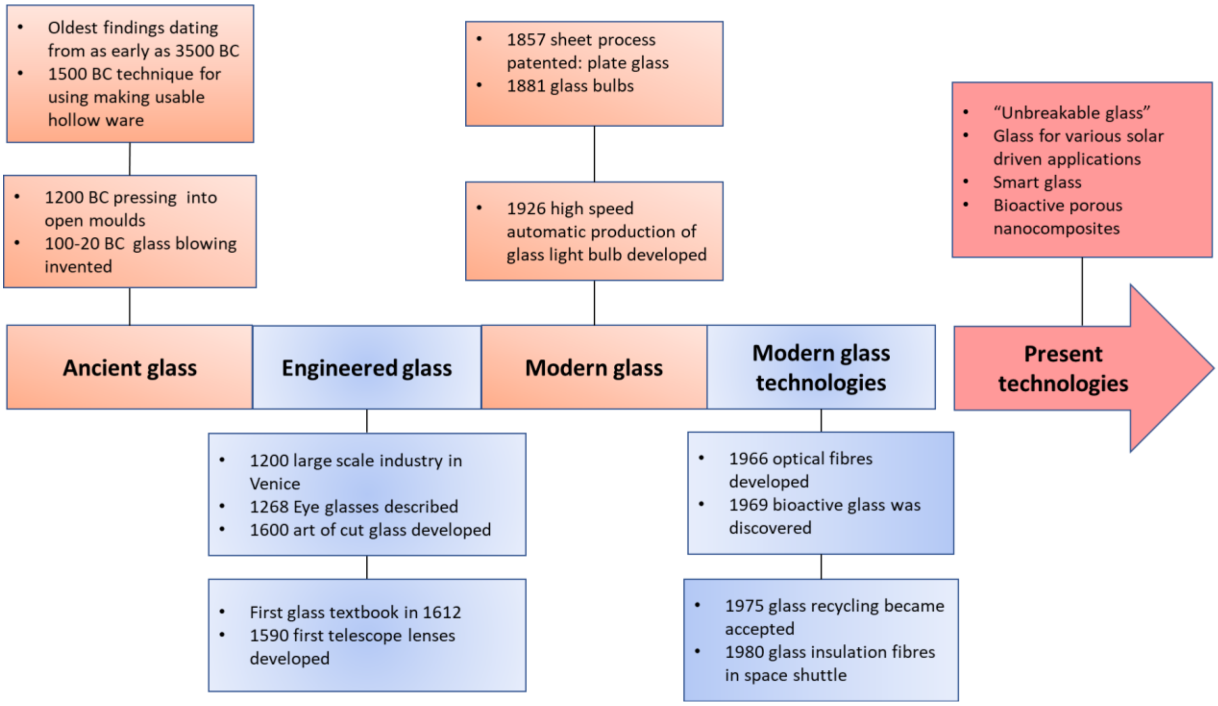

Figure 1: **Major milestones from the glass history (Source: Authors based on[3]).**

In this systematic review, we explore a critical issue related to the future of glass: decarbonization. Through a "sociotechnical" lens, the study asks five key questions to help inform further academic research, industry, and policy makers in developing decarbonisation pathways for glass. What alternatives exist to abate the climate effects of glass and thus make the full life cycle of glass more sustainable? What are the key determinants of energy and carbon from glass? What technical innovations have been identified to make glass manufacturing low to zero carbon? What benefits will amass from more carbon-friendly process in glass manufacturing, and what barriers will need tackling? To examine these questions, this study presents the findings of a comprehensive and critical systematic review of 701 studies. It utilizes a sociotechnical lens[15 16] that scrutinises the manufacturing and use of glass across multiple sectors (including buildings, vehicles, construction, electronics, and renewable energy), and options for decarbonization (including CCUS, efficient heating, hydrogen, recycling, electrification and other emerging innovations).

The article proceeds as follows. **Section 2** offers a comprehensive background on the process of glass making, the progress in terms of energy efficiency, and properties of glass along with its categorization. In **Section 3**, we present the research design, here, we do not only discuss why we have implemented a critical and systematic review approach, but also why we studied the glass industry through a sociotechnical lens. **Section 4** presents the energy use and emissions emerging from the glass industry whilst **Section 5**, discusses the current uses of glass within the industrial society. It is in this section that we discuss and examine glass applications in buildings, transport, electronics and other sectors. **Section 6** presents nine approaches to decarbonise the glass industry, and more than 30 complementary technologies and processes to improve energy efficiency during the glass making process. We shift our attention, in **Section 7** and identify barriers and challenges to decarbonize the industry, while **Section 8** presents four high potential avenues for future research. **Section 9**, concludes.

2. Background: Glass processes and efficiency progress

In this section we first describe the process of glass making, then we discuss the evolution of the glass industry in terms of efficiency. Next, we present glass properties along with glass applications, to later offer an overview of the glass market worldwide. To provide better context for the discussion to come, **Table 1** illustrates the multiple sectors existing in the glass industry.

Table 1: **Glass sectors and key characteristics**. (**Source: authors, compiled from**[17] [18] [24] [25]).

Sector	Characteristics
Container glass	Container glass is produced from a soda-lime preparation. This sector includes bottles for soft drinks, spirits, wines and beers, along with wide neck jars for the food industry. Another vital part of this sector constitutes high-value containers for the perfumes/cosmetics and pharmaceutical industries. . Some of the advantages of these glass containers are their inert chemical resistance and barrier properties (i.e., thus preserving the contents), appeal and aesthetics for brand identification, recyclability, and easy to sterilise.
Flat glass	Two types of flat glass exist, rolled and flat. The first is patterned or wired (i.e., reinforced) glass. The second is used in applications where light is dispersed, such as glass partitions, windows, greenhouses, photovoltaic panels and bathroom windows. The main markets for flat glass are the buildings and automotive sectors. Rolled and flat glass manufacturing is a capital-intensive activity since both require long-term investment, substantial financial resources and highly technical skills. The capital cost of plant ranges from €70 million to €200 million. These plants operate continuously, 365 days per years as the glass flows liquid through the plants systems. Manufacturing is limited to a number of well-known international companies
Continuous filament glass fibre (CFGF)	This is the smallest glass sector in terms of tonnage. However, CFGF products have a high value to mass ratio and are supplied in various forms, including chopped strands, mats, roving, yarns, milled fibres, fabrics and tissues and are used in thermosetting and thermoplastic resins. CFGB main markets are the building, automotive, transport and the electrical and electronics sectors.
Domestic glass	this is the smallest segment in the glass industry by output and represents about 4% of total output in the EU. It covers glass cookware, tableware, and decorative items. Products range from bulk consumer goods such as drinking glass to high-value lead crystal decanters and goblets. Regarding production techniques, these vary from manual methods to completely automated.
Special glass	This is an extensive sector with immense market value. It covers funnels and panels, cathode ray tubes (CRT), lighting bulbs and tubes, borosilicate glass tubes, laboratory and technical glassware, borosilicate and ceramic glass for cooking, quartz glass, glass for the electronics industry (e.g., LCD) and optical glass.
Mineral wool	The sector covers stone and glass wool insulating materials. The main products are pipe insulation, low-density insulation rolls, loose wool for blowing, medium and high-density pipe insulation, low-density insulation rolls and medium and high-density slabs. These products are used in fire protection, acoustics (insulation and sound absorption), building thermal insulation (roofs, floors, walls, etc.), ventilation and heating applications, industrial (technical) installations (vessels, chemical plant, process pipework, marine and offshore),

	and in inert growing media and soil conditioning. The building industry, is the largest application of this glass, representing about70 % of total outputs.
High-temperature insulation wools	In this sector the HTI wools are produced with the sol-gel method (e.g., polycrystalline alumina wools-PCW). The products made from HTI wools are sold to traditional heavy industries, such as the petrochemical, chemical, glass, ceramics iron and steel, cement and non-ferrous metals. HTI wool products have high value and are economically transported worldwide. HTI wools costs are mainly due to energy, labour and raw materials.
Glass frit and enamel frit	Glass frit is mostly used in ceramic glazes and pigment applications. Glass frit when fired, provide a waterproof, decorative and protective coating. Glass enamel frit main is used to coat metal surfaces resulting in a physical and chemical resistant surface. They are high value, low-volume products, with relatively low transport costs of the total product price.

2.1 Making glass

Glass involves, as illustrated in **Figure 2,** five main processes: mixing, melting, forming, annealing and finishing[21]. Glass production requires to be a continuous process, and for economic reasons, the melting tanks must function without interruption for several years, in some cases, more than twenty. All steps in the manufacturing process must be carefully controlled[22] and regardless of the type of glass, the production processes share similarities [23] [24] [25]. The main ingredients for the majority of industrially produced glass is soda-lime, sand, heat, and then cooling the material[3] [26]. Most commercial glass is made from soda-lime glass formulation of lime (CaO), soda (Na_2O), and silica (SiO_2), with small amounts of magnesia (MgO), alumina (Al_2O_3), and other minor ingredients.

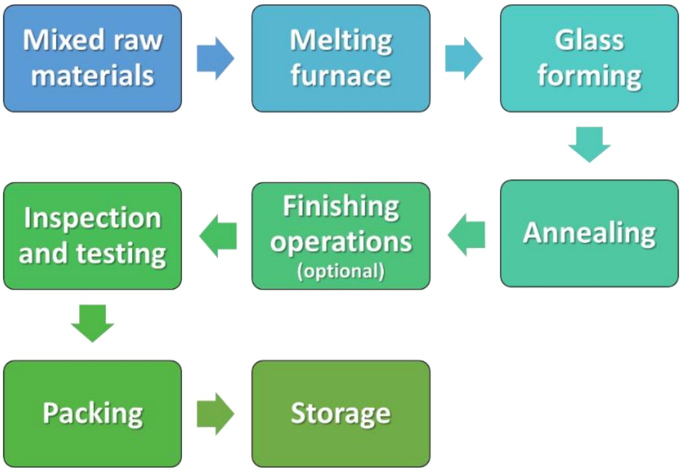

Figure 2: Stages for producing glass. (Source: authors).

All production processes start with sourcing the material for glass (as **Figure 3** shows), which can be either a raw material like ground-up waste glass (called cullet) or silica sand[27]. The raw materials used are decided by the function of the final glass and/or in the melting process. Materials, are divided into different categories: 1) fining agents to remove the bubbles from the melt, 2) colouring elements, 3) redox-active compounds to reduce the glass melt or oxidize it, 3) network formers, network modifiers, intermediates, and melting accelerants (for a further exploration of each, *cf.* Hubert[22]). Once the materials are procured, preparing and mixing ingredients in a batch for the melting furnace takes place[28]. This glass batch comprises stabilizers, sometimes colorants, formers, and fluxes, each of which can influence the properties of the final glass product. In this stage, materials are classed by grain size, weighed, and then blended[29]. Batch preparation uses electricity for transport, mixing, and the accumulation of materials in the plant[30].

Next comes the melting stage, a process that requires a minimum energy input of around 2.6MJ/kg glass (or 2.6GJ/t) for soda-lime-silicate glass[22]. Once the batch is prepared, it is transferred to the furnace, melted and withdrawn at a controlled rate. Melting is responsible for consuming more than half of the energy use in glass production[31] and releasing the carbonates contained in the glass[32]. At this stage, different percentages of total process energy are consumed depending on glass type. For instance, during the production of glass containers, this stage typically consumes about 75%–85% of total energy[33]. To carry out this process and melt the glass batch material, most producers either use direct electrical heating, combustion heating, or both.

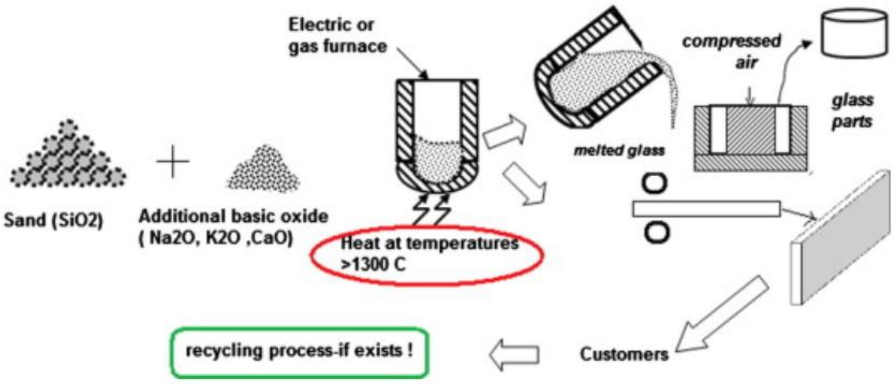

Figure 3: steps for glass production (Source: reproduced from[34]).

Molten glass is then conditioned in a forehearth. The forehearth controls and maintains temperature on the journey to the forming process. Forming equipment varies by final glass product being manufactured[33]. The conditioning and forming steps consume between one eighth and one-third of the energy used in glass manufacturing process, depending on the glass type. Natural gas is typically used for the heating, whereas electricity is used to power the fans, mechanical pressing and conveyors[29]. The glass, at this stage, can be either formed through a continuous shaping process for flat glass or fiberglass, or alternatively, can be delivered in “gobs” for glass container production[33].

2.2 Glass efficiency: progress and history

The technology developed for melting glass has gone through six stages (see **Figure 4**)[35] [36]. This evolution of the process is illustrated with manufacturing glass in open pits around 3000 BC until the all-oxygen-fired glass melting furnaces in the 1970s. In fact, between 1960 and 2010, energy efficiency improved by over 50%[37]. For instance, between 2006 and 2010, energy consumption for melting decreased from 12.6 MJ/kg to 8.5 MJ/kg respectively.[25] Unfortunately, progress in energy efficiency since 2010 has slowed down dramatically since it is often not an investing priority and is generally perceived as additional business cost [38] with evidence indicating that overall energy intensity is most likely to remain flat until 2030, with expected reductions in energy consumption to significantly occur after 2050[39].

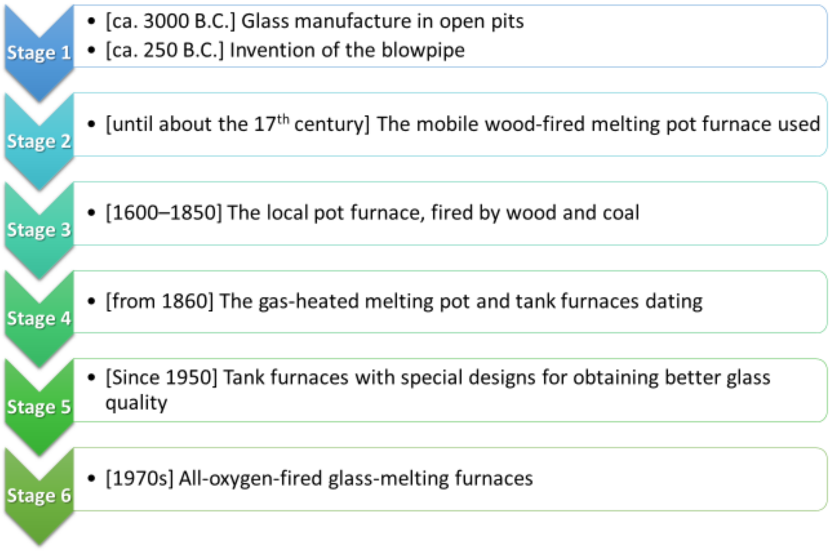

Figure 4: Melting glass technologies illustrated in six stages (Source: authors).

Furnaces are key in determining the energy intensity and efficiency of glass production, since the highest proportion of energy from the overall process is used by them[40]. A glass furnace consists of a chemical reactor in which raw materials like soda ash and silicates are transformed to glass[21]. There are four main melting furnace in the glass industry: 1) regenerative, 2) recuperative, 3) oxy-fuel and 4) electric.[41] Furnaces often run at average temperatures between 1500 °C and 1600 °C[21] and their energy efficiency depends on several[42 43 24].

The efficiency of furnaces has been improved over the last forty years. Between 1979 and 2003 the average furnace energy consumption improved from 3.2 MWh per tonne to 1.4 MWh per tonne (gross basis) [44]. Some argue that a key driver for efficiency in furnaces is that they are equipped with energy recuperation systems[22] while others suggest that computational modelling has been the key determinant in making more efficient furnaces[45].

2.3 Properties of glass and distinguishing features

A wide variety of glass end-uses and diverse glass properties have made it hard for scientists to find a holistic definition for glass. However, for the purposes of this review, Shelby's definition seems appropriate: "Glass is a solid that possesses no long-range atomic order and, upon heating, gradually softens to the molten state"[46]. Glass is non-biodegradable, although it can be endlessly recycled through different techniques without affecting its chemistry[47 48]. Glass properties (see **Table 2**) are unique to the chemical composition of the glass—changing one of its properties often affects the others. Hence, when selecting glass for a specific product, the thermal, chemical, mechanical, and optical properties are important[10].

Table 2: The valuable industrial properties of glass. (Source: authors compilation of [10] [29]).

Property	Description
Chemical	A highly resistant material to chemical attacks. It stores food and beverages for many years without corrosion effects. Only a handful of chemicals aggressively attack glass, namely: phosphoric acid, hot alkali solutions, hydrofluoric acid, and superheated water.
Elasticity	A perfectly elastic material in that after stretching it returns to its original shape when the force is removed. It breaks only when the force applied surpasses its fracture strength.

Strength	Is stiff and breaks rather than deforms when exposed to severe impacts. It is very strong in compression. Furthermore, chemical modification laminating or thermal tempering increases the tensile strength of glass.
Hardness	Has a hardness comparable to steel, and it can endure significant abrasion over time.
Optical	Is translucent or transparent to light. Depending on the glass treatment it can transmit either ultraviolet or infrared light while absorbing visible light. It can bend light when used as a lens.
Electrical	Is a good insulator and provides high electrical resistance.
Thermal	It possesses low thermal expansion and high thermal shock resistance.

Other common glass types are summarised in **Table 3** and include borosilicate, lead crystal glass and speciality glass[49]. Speciality glass, including fiberglass, are made using borosilicate or aluminium borosilicate, which consist primarily of boric oxides and silica, along with other minor additions for refining, decolorization and incorporation of special properties[50 51].

Table 3: An overview of glass families, key components and common applications and uses. (Source: Authors, modification of [22]).

Glass family	Key components	Common Applications and uses
Soda lime	$Na_2O \cdot CaO \cdot SiO_2Na_2O \cdot CaO \cdot SiO_2$	Flat glass (windows), tableware, Container glass (bottles and jars) Lamp glass (lighting), lenses
Lead crystal glass	$PbO \cdot K_2O \cdot SiO_2PbO \cdot K_2O \cdot SiO_2$	Glass primarily used for decorative purposes, such as art glass, tableware, enamels
Borosilicate	$Na_2O \cdot B_2O_3 \cdot SiO_2Na2O \cdot B_2O_3 \cdot SiO_2$	Headlights, Laboratory and cooking utensils materials and tubing
Speciality glass	SiO_2	Telecommunications, halogen lighting Lab equipment, optical elements
	$Na_2O \cdot CaO \cdot B_2O_3 \cdot SiO_2Na_2O \cdot CaO \cdot B_2O_3 \cdot SiO_2$	Construction materials such as glass wool for insulation and glass fibre for reinforcement
	$CaO \cdot Al_2O_3 \cdot B2O_3 \cdot SiO_2CaO \cdot Al_2O3 \cdot B_2O_3 \cdot SiO_2$ (can also be boron-free)	Fibres used in circuit boards reinforcement for plastics and polymers
	$MgO \cdot Al_2O_3 \cdot SiO_2MgO \cdot Al_2O_3 \cdot SiO_2$	Glass fibre used for reinforcement
	$Al2O_3 \cdot CaO \cdot B_2O_3 \cdot BaO \cdot SiO_2Al_2O_3 \cdot CaO \cdot B_2O_3 \cdot BaO \cdot SiO_2$	Substrate glass for displays (LCD televisions, personal computers and mobile phones)

2.4 Industrial and market structure

The glass industry, worldwide, comprised more than 1270 glass companies and groups[52] and was valued at $129.2 billion US in 2019. **Table 4** presents key market attributes of each of the most profitable glass sectors.

Table 4 key market attributes of glass by different sectors. (Source: authors compiled from [19 38 43 53 54 55 56 57 58]).

Sector	Market attributes
Flat glass	Accounts for around 30% of total glass production, that is over 50 million tonnes, representing a value at the level of primary manufacture of approximately €22 billion. 29 million tonnes were destined for float glass, 3 million tonnes for sheet glass, and 2 million tonnes for rolled glass from the total global market demand, with China, Europe, and North America leading the flat glass market. This sector's global market is expected to continue increasing due to the growth in the construction and automotive industries and the rising demand for energy-efficient glass.
Container glass	The packaging market is expected to grow with a CAGR of 5% between 2019–2023 due to an increasing alcohol beverage market in the Asia Pacific region. Currently, this region

	represents 37% of the world's demand, while the European market experienced growth of around 2.1% CAGR in the period 2014–18, reaching a total of 1.043 trillion packs. The global market for container glass packaging was valued at more than €50.75 billion in 2019. In the EU, the beverage sector represents two thirds of the total tonnage of glass packaging containers.
Fiberglass	This sector represents 10% of the world glass production and is expected to grow with the expansion of the wind energy market, electronics, construction and infrastructure and fiberglass composites for the automotive and bathroom industries. This market is expected to grow from €9.77 billion in 2020 to €12.14 billion by 2025, at a CAGR of 4.5% during the same time period.
Speciality glass	Together with fiberglass, this market represents 10% of the world's glass production and is expected to grow 7% and cross €29.72 Billion by 2025. This growth is attributed to high demand in the electronics and telecommunication industries. Within this sector, photonics holds great potential, with an estimated market value of over €600 billion. Most growth will occur in laser-based manufacturing, medical technologies and life sciences, lighting, and optical communications.

Research estimates that the glass industry will reach USD 180.94 billion by 2027, with a compound annual growth rate of 4.3% during 2020-2027. This industry is continuously growing, most notably, the flat glass family[53], which is expected to produce more than 65 MT by 2022[49]. A key characteristic of the glass industry is that more than 90% of its products are sold to other industries[54]. **Figure 5** illustrates glass markets according to their sector. Thus, glass manufacturing is highly dependent on the building construction sector, car manufacturing, and the food and beverage industry[59]. In fact, more than 80% of the total mass of glass produced worldwide is either in the form of pharmaceutical products, plane glass for automobiles, building construction and canisters for food packaging[60].

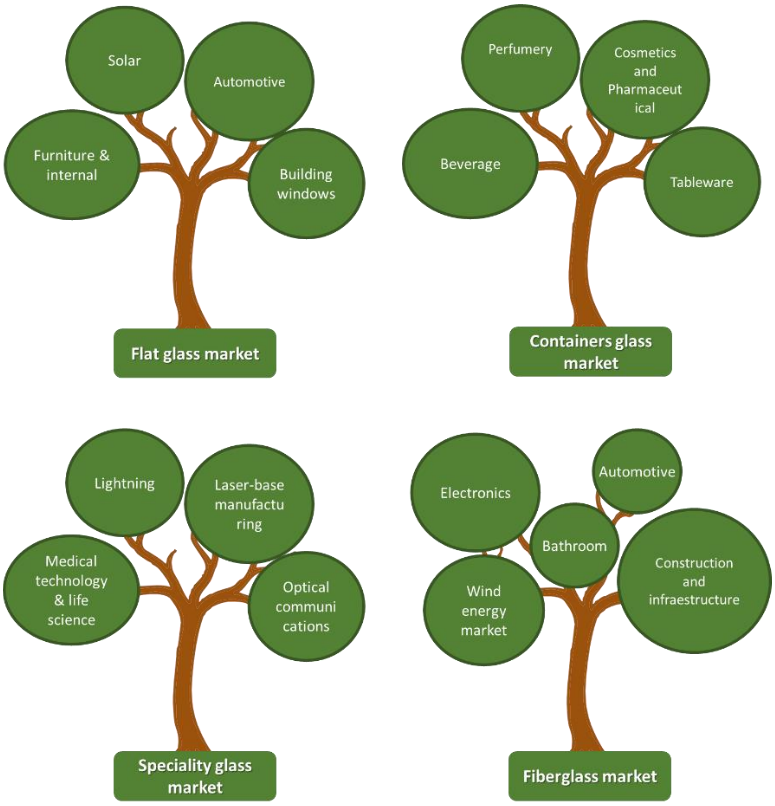

Figure 5: **Glass sectors and markets (Source: authors).**

3. Research design and conceptual approach

To explore the decarbonization of glass, we replicated methods from Sovacool *et al.,*[15] [16] and utilized a systematic searching protocol with a critical review approach and the guiding conceptual perspective of sociotechnical systems.

3.1 Critical and systematic review approach

We classify our review as both systematic and critical since a "critical review" seeks to prove that a research team has broadly scoured the literature and critically assessed its quality[61]. It goes beyond unfolding the literature to interpreting it and making evaluative statements on the possible research gaps and quality of evidence. To do so, it presents analyses, and synthesizes a variety of material from various sources. A critical review offers the possibility to "take stock" and evaluate what is of value within a given dimension or across multiple bodies of evidence associated with a particular topic or research question. It offers both a "launch pad" for conceptual novelty and an empirical "testing" ground to judge the strength of evidence.

Assuming that a weakness of critical reviews is that they do not always prove the systematic nature of more rigorous approaches to reviewing, we also made our review "systematic." This approach to a review offers several advantages over a traditional literature review[62] [63]. In particular, this approach provides the following benefits:

- a focused investigation that avoids inconclusive results and wide-ranging discussion;
- the avoidance of discerning and opportunistic evidence;
- replicability through the documenting of study inclusion;
- the skills to discriminate between sound and unsound studies, therefore assessing methodological quality; and
- increased transparency, which decreases subjectivity and bias while presenting results.

Systematic reviews, moreover, minimize unintentional bias and encourage diversity. For these reasons, a number of studies have called for greater use of systematic reviews in the domains of the environment and energy, energy social science and climate change[64] [65] [66].

3.2 Searching protocol and analytical parameters

To guide our critical and systematic review, we relied on three distinct classes of search terms as **Figure 6** summarizes. We then executed these search permutations in twelve separate databases (3,432 search strings in total) to capture the state-of-the-art research.

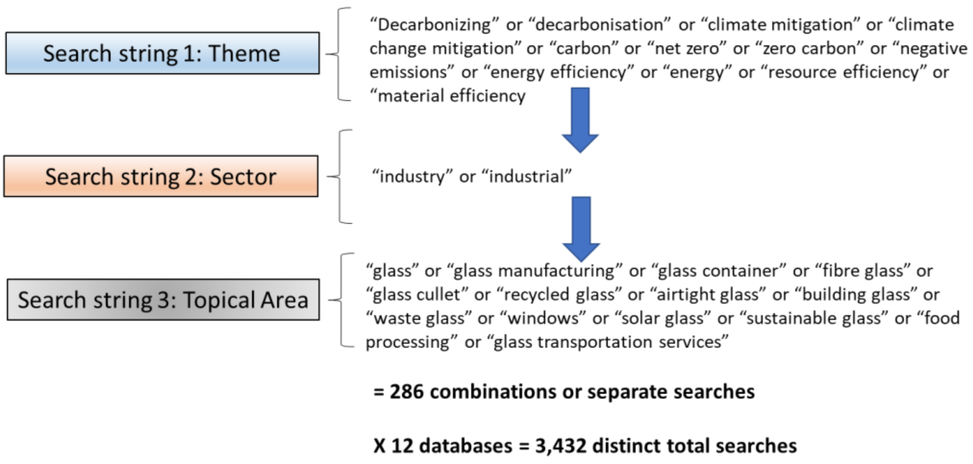

Figure 6: Summary of critical and systematic review search terms and parameters (Source: Authors)

Table 5 presents our results. It shows that while our generic searches resulted in 4,635,883 possibly relevant documents, this fell to a final sample of the 701 most pertinent studies. After screening them for relevance (they had to address the precise topic of climate change mitigation and/or decarbonization), originality (we adjusted the results to eliminate duplicates), and recency (they had to be published after 2000), this number fell to 375 studies. We cite the majority of these studies throughout the review.

Table 5: Summary of critical and systematic review search results and final documents (Source: Authors)

Database	**Main topical area of database**	**Initial search results**	**Deemed relevant after screening titles, keywords, and abstracts**	**Deemed relevant after scanning full study**	**Number of duplications**	**Total**
ScienceDirect	General science, energy studies, geography, business studies	73,629	196	124	-	124
JSTOR	Social science	4,884	31	18	2	16
Project Muse	Social science	16,865	29	7	0	7
Hein Online	Law and legal studies	20,065	31	8	0	8
PubMed	Medicine and life sciences	27	7	7	2	5
SpringerLink	General science, business and area studies	58,144	84	50	0	50
Taylor & Francis Online	General science	8,464	32	19	0	19
Wiley Blackwell (Wiley Online Library)	General science, area studies	14,090	45	22	0	22
Sage Journals	General science, area studies	2686	10	7	0	7

National Academies Publications (nap.edu)	General science	1,599,418	7	1	0	1
Targeted internet searches	White papers, reports, grey literature (e.g., International Energy Agency, International Renewable Energy Agency, World Bank, UN agencies, and the online OECD library)	2,438,222	150	96	5	91
Google scholar	General science	369,389	79	44	19	25
Total		**4,635,883**	**701**	**405**	**24**	**375**

3.3 Analytical frame of sociotechnical systems

To help guide and structure our results from this body of 375 final documents, we used the conceptual approach of sociotechnical systems[67] [68]. **As Figure 6** illustrates, this method considers the glass sector as far more than just physical products (a window, glass or a bottle of beer/wine). Rather, this frame views the entire set of social and technical systems involved in making, distributing, and using glass. This includes not only the furnaces where glass is manufactured and how glass bottles are delivered and shipped to stores, but also issues pertaining to local regulations of glass waste and management and consumers' preferences. **Figure 7** reorganizes the sociotechnical elements of glass system by supply chain, as well as the policy-regulatory dimension (showing the intersection of social organizations, local infrastructure and legislation, progress on its science and technology, the environment, and markets). The sociotechnical system for glass, therefore, encompasses dimensions such as the construction industry, automotive, food and beverages, renewable energies, electronics, health, wellbeing and beauty, energy efficiency and entertainment. From this perspective, we argue that the glass industry touches upon so many aspects of our life that it should be approached from a sociotechnical system.

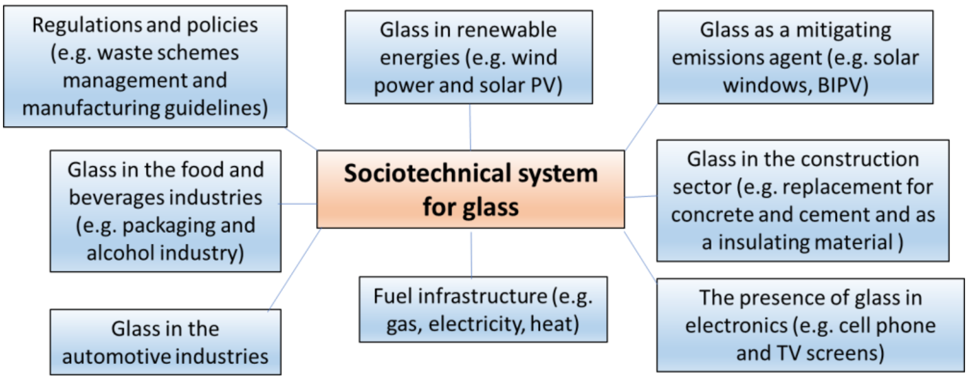

Figure 7: Framing glass as a sociotechnical system (Source: authors)

Though not all studies in our sample employ this rubric of a sociotechnical system, we use it through the research to structure results and return to it in the conclusion section. In the following sections, the different glass applications are discussed in a comprehensive and not repetitive way.

4. Energy use and carbon emissions associated with glass

Industry is one of the most challenging sectors to decarbonize. It is responsible for over 30% of all greenhouse gas (GHG) emissions, of which the majority are emitted by energy-intensive industries[69]. Glass, is definitely one of these subsectors.

4.1 Energy intensity of glass manufacturing

The glass industry, holds one of the highest production volumes per capita worldwide,[53] is also considered an energy-intensive industry due to its high share of energy per tonne of product[28] [70] [71] [72]. For instance, producing 1 kg of glass in a gas-fired furnace generates about 0.6 kilograms of CO_2 of which, 0.45 kilograms emerges from fossil fuels combustion and 0.15 kilograms from the dissociation of carbonate raw[59]. The principal consumers of electricity in a container glass plant -after the furnaces- are the compressors used to provide air for the glass-forming processes[73]. Pumps are yet another instrument that uses electricity, mostly for bag-filtration to remove particulate pollution from conveyors, motors, electric fans, exhaust gases, laminating, glass coating equipment and packaging[74]. The energy use that consolidates the European and the USA glass industries is dominated by natural gas, which often represents around 75-85%, followed by electricity use rounding 10-15% and the remaining 5-10% is composed by fossil fuels[75] [76] [77] [78].

Looking solely at the Chinese glass industry, its total energy consumption was 7.6 million tons of coal during 2005, and increased to 8.9 and 9.6 million tons of coal by 2009 and 2010, respectively[25]. In India, which is among the top 15 major glass markets, the glass industry total energy consumption is about 1.17 Mtoe[79]. In the USA, glass manufacturing represented 1% of total industrial energy use[76].

A key challenge to lower the energy intensity of the glass industry is the lack of technology to operate large-scale float glass furnaces using only electricity. The vast majority of best-performing installations continue to be powered through a mix of fossil fuels and electrical boosts. In these circumstances, there are two scenarios. Those who argue that with the current technologies available, it would be highly challenging to achieve an 80% decrease in CO_2 emissions as established in the EU roadmap for industrial operations and those with a more positive view. The first group postulates that completing this goal will require significant breakthroughs in thermo-dynamic science and raw material use, along with significant developments of Carbon Capture Utilisation and Storage (CCUS), hydrogen, and options to electrify industry further. Based on these assumptions, the decarbonization of the glass manufacturing industry is thus projected to follow a slow trajectory in the following 20 to 30 years as infrastructures and technologies are put in place and then rolled out to all installations[20]. On the other are hand, there are those with a more optimistic view that suggests that fuel combustion emissions can be eliminated in a more challenging but possible way. Madeddu *et al*. indicate that emissions can be cut by 78% through deep electrification and the installation of hybrid technologies to allow switching from electricity to gas depending on the prices. In tandem with the expansion of onsite renewable electricity generation to provide greater autonomy and lower risks due to price volatility. By implementing this strategy, 78% of the energy demand could be electrifiable with technologies already established, while 99% of electrification can be achieved if technologies currently under development are employed[80].

4.2 Process and carbon emissions from the glass industry

Due to its energy intensity, glass also involves a series of related process and direct emissions. The primary process emissions include CO_2 as well as NO_x, which arise from high temperature combustion in air, and SO_x, which chiefly arises from the fuel and the fining processes for sulphur-fined glass. Although presented in lower quantities, there are other contaminants, such as KOH and NaOH, and harmful gases such as HF and HCl. In the manufacturing of borate species (alkali borates such as KBO_2 and $NaBO_2$, or metaboric acid HBO_2) borosilicate glass can also be found[22].

Direct emissions mostly arise from the combustion of fossil fuel and raw material degradation in the furnace (process emissions) and indirect emissions emerge from the electricity originated in the grid. The carbon intensity of this industry becomes more notorious when the container and flat glass sectors (which combined account for 80% of glass production) emit over 60 million tonne of CO_2 emissions per year,[28] which is higher than the annual emissions from Portugal[31]. In the EU alone, the glass industry emits more than 20 million tonnes of CO_2 per year[81] with annual energy consumption of more than 350 PJ,[77] representing around 2% of the verified emissions of all stationary installations of the European Union and approximately 6% of industrial emissions, not including combustion[82]. Meanwhile, in the UK, the glass industry emitted 1.7 million tonnes of carbon dioxide, with a further 0.5 million tonnes/year emitted in electricity production for use within the glass sector[75]. A generalized breakdown of emissions resulting from the UK glass industry is as follows: around 24% of CO_2 emissions results from primary electricity generation, while 18% of CO_2 emissions is released from raw materials. The remaining 58% emerges from fossil fuel combustion[17].

4.3 Other environmental impacts of glass

The environmental challenges with glass, however, are not limited to emissions alone. Although the raw materials for creating glass are often thought to be unlimited, the amounts of sand and gravel being demanded are now so large, that these exceed their rate of natural renewal, and by the mid-21st century, estimations suggest that production may no longer be able to meet demand[83]. Even though precise figures are not available, it is estimated that somewhere between 32–50 billion tonnes are used globally each year, primarily, to produce materials such as glass, electronic devices and concrete[84] [85]. The high demand of these materials most likely will persist in the future due to the high levels of urbanization, with the UN estimating that by 2060, annual demand will reach 82 billion tonnes[86]. Certainly, the unsustainable consumption of gravel and sand to furnish glass and other materials is not only devastating these finite resources, but also, due to the energy intensive processes to manufacture these products emissions most likely increase, unless we find methods to mitigate emissions from industries.

5. Current uses of glass within industrial society

In this section we focus on the uses of glass within the industrial society. Here, we explore a number of glass technologies used in buildings, automotive, construction, electronics, solar PV and wind turbines and the packaging sectors.

5.1 Glass technologies for buildings

Several glass technologies can improve buildings' efficiency. For instance, electrochromic (EC) windows provide users with better visual and thermal comfort while facilitating a climate adaptive building shell completely adjustable to any weather condition or users' preferences[87]. EC has proved to be 45% more efficient than single-pane static glazing, a recurrent material in the existing building stock. EC glass can reduce carbon emissions by 35% in new constructions and around 50% in renovation projects[88]. Other studies suggest that the low-emittance (low-E) glass improves the thermal/optical performance of the glass, making it reflect up to 90% of infrared radiation while enabling visible light to enter. low-E glass, thus, can reduce unwanted heat gain in the summer and heat loss in winter[89]. The use of solar thermal façades represents another technology to improve thermal performance and accomplishes energy savings of between 50% and 70 % for retrofitting, and 20 % and 30 % for new low energy buildings[90]. Solar control glazing contributes to mitigating emissions by lessening the reliance on air conditioning while reducing the amount of heat energy able to enter the building and maintaining high levels of transparency[91].

Other uses of glass that help mitigate emissions in buildings are solar windows that use thermochromism.[92] This technology operates by absorbing the sunlight as it is transmitted through the window and transforms it into electricity. The windows act like solar cells, providing a flexible clean energy solution for modern building design. The technology allows significant reductions of both heating energy demand in winter and cooling energy demand in the summer, corresponding to an increase in performance of over 20%[93]. Other innovations come in the form of "liquid windows," a technology consisting of hydrogel-based liquid within glass panels. Liquid windows can block sunlight and keep the building cool while absorbing heat to liberate it during day or night to save energy gradually. This technology can reduce energy consumption in buildings by over 45% compared to traditional glass windows[94]. There are other technologies meant to progressively replace traditional windows,[95] such as smart windows. These technologies, can provide energy savings of over 8% in total energy consumption and 18% in cooling loads[96].

Other commercially available glass products include glass-on-glass building-integrated photovoltaics (BIPV). These systems can fully integrate with façade window systems and operate in rooftop skylights of buildings[97]. The latter application, for instance, generates energy while controlling the amount of direct sunlight entering the building. This results in reducing cooling loads and preventing heating during bright, glaring days[98]. The relevance of this technology is such that BIPV is estimated to exceed 7.6 million square meters by the end of 2021[99] and is expected to reach a market value of USD 8.7 billion by 2026, representing a CAGR of 16% during the forecast period.[100] Within the buildings' structure, BIPV applications will be dominated by rooftop installations, with almost 80% of the market share in contrast to 20% for façade applications[101]. Indeed, integrating BIPV systems into "green" buildings can deliver an additional energy generation source located within the building's envelope, with the key advantage that energy generated is accessible immediately at the point of use[102].

5.2 Glass in the automotive sector

Glass is also a key component in the automotive industry, accordingly, glass represents approximately 3% (by mass) of the total composition of a car[103]. In 2020, around 1.3 million tonnes of glass were used in Europe to manufacture windscreens, side and rear-side glazing, backlights, and sunroofs[93]. Due to the global increase for vehicles, the flat glass automotive industry is expected to register a CAGR of around 7%, during the forecast period of 2019-2024[104]. The most common composites used in the automotive industry include those based on natural fibres, carbon fibres and glass fibres,[105] with vehicle production being the largest consumer of the latter[106]. Flat glass developments can help reduce fuel consumption with lighter glazing[107]. In addition, with electric cars entering the mass market, vehicle insulation is becoming increasingly important for reducing power consumption for electrical heating and cooling of vehicles[108]. Indeed, further innovations about solar control glass have minimised the necessity for air conditioning in cars (which is a significant energy consumer in road transport), reducing emissions from conventional vehicles while increasing EV range[20]. In the near future, roof-integrated photovoltaic may play a key role in clean mobility[93].

In terms of building cars, glass fibre composites are preferred over other materials for mass-market applications due to their cost (E-glass fibre costs around US $1.00-$1.50/Kilogram)[109]. However, other glass properties such as stiffness and toughness to resist operating loads makes it an ideal structural component for brackets and bumper beams[110]. From an LCA perspective, compared to other materials such as carbon fibre composites, glass fibre composites have lower material and manufacturing costs. The downside is that as a glass reinforcement, glass fibres are prone to ageing and deterioration due to moisture absorption in humid environments[111]. This has adverse effects on durability. Other studies compared talc-reinforced composites and hollow fiberglass reinforced composites. The results show that the latter has a lower environmental impact relative to the talc-reinforced composites for automobiles[112].

There are, however, specific problems with glass in vehicles. The one that stands out the most is recycling; due to glazing methods, dismantling this waste stream is complex. The majority of end-of-life vehicle glass is landfilled if not recycled as an aggregate substitute[103]. Methods to recycle fiberglass exists, for instance, through mechanical methods and thermal. However, both approaches are energy intensive, and the fact that the particles of aggregate are highly abrasive negatively impacts the equipment's comminution. Once the fibreglass is recycled it can be used in other products. For example, one EU project used recycled fibreglass to manufacture reinforced thermoplastics for specific applications in the automotive industry. The results show that if fully applied to the 150,000 tonnes of fibreglass waste produced in Europe every year, this approach would save 21,900 tons of CO_2 emissions[113].

Regardless of these innovative approaches, recycling fibreglass remains a major issue, thus, encountering glass substitutes could provide a more sustainable alternative. For instance, basalt fibres possess more favourable properties for the automotive industry than fibre glass[105]. This is also the case of grass polybutylene succinate (SG–PBS)[114]. Nanocomposites are another option, since these have advantages over fibre and mineral glass in terms of strength, durability, reliability and corrosion and thermal resistance. Due to these properties, some argue that nanocomposites can substitute glass and metal components in the near future and help the automotive industry save fuel and produce more durable vehicles of a higher quality[115].

5.3 Glass in the construction sector

Some have explored the role of glass in various structural and insulating applications[116] [117]. On a similar track, others have used waste glass as fine aggregate replacement in self compacting concrete (SCC). Their results indicate that waste glass owns great potential to be used in SCC to improve mechanical strength,[118] leading to the mitigation of emissions from one of the most polluting industries. Alani *et al.*,[119] suggest using glass screeds to replace sand screeds, which not only reduces structural energy consumption but also facilitates the recycling of what otherwise would turn into waste or to an extremely difficult material to process. Regarding applications in road construction, waste glass in asphalt concrete can be used in varied forms, including fibres, large or small particles and powder. Therefore, a significant part of waste glass could be diverted from landfills to be used as an aggregate substitute for asphalt concrete[120]. Others have explored the use of waste glass sludge (WGS) in the manufacturing of burnt clay bricks. Their findings show that crushed waste glass can lower the firing temperature and improve the physical-mechanical and durability properties of clay bricks in terms of porosity and water absorption[121] [122] [123]. Finally, Luhar and team[48] found that recycled glass incorporated into fly ash-based geopolymer is a suitable substitute for developing low energy and low carbon composites.

Glass can be used as a cement replacement in Portland cement concrete[124]. Utilizing glass to partially replace Portland cement materials provides—somewhat better—environmental results when compared to traditional glass recycling[125]. For instance, research indicates that the production of cement with glass powder from locally generated waste glass can mitigate 12% of GHG emissions and reduced by 15% energy consumption from the cement industry[126]. Similarly, through a LCA in cement kilns, Jiang and colleagues found that notable energy savings are achieved in conventional concrete production when glass powder was included as a pozzolanic material[127].

Research on this area shows that using both nano-silica (3% cement content by weight) and waste glass powder (up to 40% by cement weight) can jointly be used in concrete applications without adverse reactions. Their results indicate that nano-silica's presence improves the physical and mechanical properties of a waste glass cement system[128]. Not only that, glass powder can be used as a filler in ultra and high-performance concrete for better performance, cost optimization, and even as a mineral additive for eco-cement production[2]. The cited study concludes that glass powder could facilitate recycling waste glass and contribute to a more circular economy[2]. Other studies also highlight the value of glass utilization in the construction industry. For instance, Hossain *et al*., [126] reported that 20% clinker replacement by glass cullet, reduced by 17% GHG emissions and 16% of energy consumption.

Research has also demonstrated that the partial replacement of Portland cement with glass powder reduced alkali-aggregate in concrete[129]. Similarly, Paris showed that 20% replacement of Portland Cement with glass powder improved cement's durability characteristics[130]. Shayan and Xu have shown that glass powder can effectively replace 20% to 30% of cement in 40 megapascal concrete without inducing detrimental effects in cement[131]. To this list, we can add other studies that show that recycled crushed glass can improve the properties of concrete, including flexural strength, workability, and Alkali-Silica reaction expansion by optimally incorporating the accurate dosage of glass recycled aggregates[132] [133] [134] [135] [136] [137] [138] [139]. These results show that glass composites as a substitute for cement in concrete or mortar had a minor or insignificant influence on its mechanical properties, and in some cases, utilising glass resulted in an improvement in the mechanical properties.

Although some studies have shown that a feasible 100% glass concrete could and has been manufactured for construction purposes[140], other studies suggest the opposite and note that glass aggregate for Portland concrete can cause expansion and cracking[124] [141]. In this vein, Maier and Durham found that waste glass decreases the workability of a concrete mixture due to the high absorption capacity of the recycled concrete along with the harshness of the waste glass[142]. This lack of consensus and inconsistencies has led to the hindered acceptance of glass in producing concrete. In response, Guo and colleagues[143], after an extensive review, conclude that current applications of concrete where glass is incorporated have shown improved mechanical properties, long-term durability, sustainability and functionality. Nevertheless, they warn that the proper selection of glass is essential to guarantee the success of applications. Therefore, they recommend selecting the appropriate particle size, type, and replacement percentage of waste glass to obtain concrete's adequate properties (e.g. hardness and porosity) and long-term durability.

5.4 Glass in electronics

E-waste is a complex material containing hazardous (e.g., mercury, chromium, biphenyl, led, cadmium, polychlorinated) and non-hazardous (e.g. glass, metals, plastics) materials[144]. In 2019, the world generated 53.6 million tonnes of e-waste, and yearly, this waste grows by 2.5 million tonnes[145]. Estimations indicate that around 5.5% of e-waste is composed of glass[146]. Printed circuit boards (PCB) that are categorized as E-waste are a common component in most electronics and contain high percentages of fibreglass [147] [148]. Although these materials represent a small percentage of the total share of e-waste (approximately 3%), their production is increasing rapidly, with forecasts estimating that the global PCB market is growing at a compound growth rate of 3.43%[147]. The main environmental issue with PCBs is that the recycling process to recover non-metal materials is complex and expensive. In addition, if this process is completed, fiberglass layers have limited application due to the size of the recovered product (15–20 mm^2)[149]. A cost-effective remedy for glass recovery, thus, consists of high-temperature thermal decomposition. However, this method remains rarely applied for PCBs[150].

Computer and TV monitors, both containing cathode-ray tubes (CRT), represent around 80% of the total electronic waste and CRTs are about one-third of the electronics waste by weight[151]. Estimations suggest that CRT embodies approximately 65% of the weight of a television or a computer monitor and is composed of 85% glass[152]. It is a common practice that collected monitors are ripped apart and treated, while CRT glass usually ends up in a distinct landfill certified for hazardous waste[151]. Due to its chemical structure, if glass within CRTs is recycled, it can be treated, processed, and re-used to make cement mortars[153] or concrete[154]. Nowadays, the production of new CRTs is almost zero (for a detailed explanation of each, see:[151]), making the TV and computer monitor industries a remarkable example of how rapid an industry can change as the transition from CRTs to LCDs took place within two years only[155]. Nevertheless, LCD screens continued using glass substrates made from alumina-borosilicate glass and other critical raw materials (e.g., indium and tin). Glass, again, is a major component of LCD panels representing around 90% by weight once the backlight unit is removed. Given the large volumes of glass produced annually for this industry, it is viable to consider glass reuse or diversion from landfill[156]. In fact, as CRTs, glass waste resulting from the production of LCDs can be used as a cement substitute to produce good quality mortars[157].

Glass is yet another key component in the smartphones industry. For instance, for an iPhone 4, glass is the heaviest component, weighting 47g in comparison to the phone’s steel at 40g only[158]. Ultra-thin curved (2.5D, 3D) glass is widely used in most smartphones with a steadily increasing market demand expecting to reach 1.9 billion units in 2022[159] and an actual service life of less than three years[160]. Like PCB, CRT, and LCD, ultra-thin curved glass is a hard to recycle material, leading to large volumes of raw glass material waste and the liberation of toxic components such as, but not limited to, arsenic and antimony oxide[161]. Due to the smartphones’ chemical composition, the recycling strategies are limited; however, remelting could be the most sensitive approach regardless of the efforts of separating materials into various types[162].

Given the increasing demand for electronics and the fundamental role glass has in its construction, it is paramount not to disregard the threats arising from landfilling e-wastes. Since Cadmium, Hg, and Pb's leakages pose serious environmental and health concerns[163]. In comparison to reclaiming glass cullet, recycling e-waste is a much more complicated process. A major challenge is mercury and fine glass particles from phosphor fractions. Most of the mercury in spent lamps are chemically bound to the phosphor powder (89%) and glass particles (8%). The same study shows that the filtered waste dust collected from crushed fluorescent tubes contains 17% rare Earth materials (primarily yttrium and Europium) and between 40%–

50% glass and non-soluble particles[164]. To this, we can add that countries that are main consumers and producers of glass do not have appropriate regulations governing low-value recyclable resources such as waste glass or waste compact fluorescent lamps[165] [166].

5.5 Glass for renewable electricity

The transition towards a low-carbon future is due to cause an intense global demand for raw materials. For example, wind and solar facilities require up to 90 times more aluminium, 15 times more concrete, and 50 times more copper, iron, and glass than equivalent fossil fuel facilities[167].

5.5.1 Glass in Solar PV

Regarding solar PV, cumulative global deployment grew from 1.4 GW in 2000 to 627 GW in 2019[168]. Certainly, photovoltaics are now a critical energy source, generating nearly 3% of global electricity, with crystalline silicon (c-Si) modules (also known as panels) constituting more than 90% of the global PV market[169]. Each of these modules contains 67% to 76% glass to build the panel's surface and provide structural integrity and protection from the environment[170] (**Figure 8** illustrates solar PV's typical structure). The specific functions of the glass component are common to all solar PV systems: glass transmits the solar radiation to an active component while simultaneously providing structural and chemical protection of the active component from the ambient conditions[3]. Therefore, we argue that not only glass is an integral component of many solar PV technologies but also is a crucial component to improve solar energy's efficiency (i.e., through anti-reflective coatings that allow more sunlight into the module)[20].

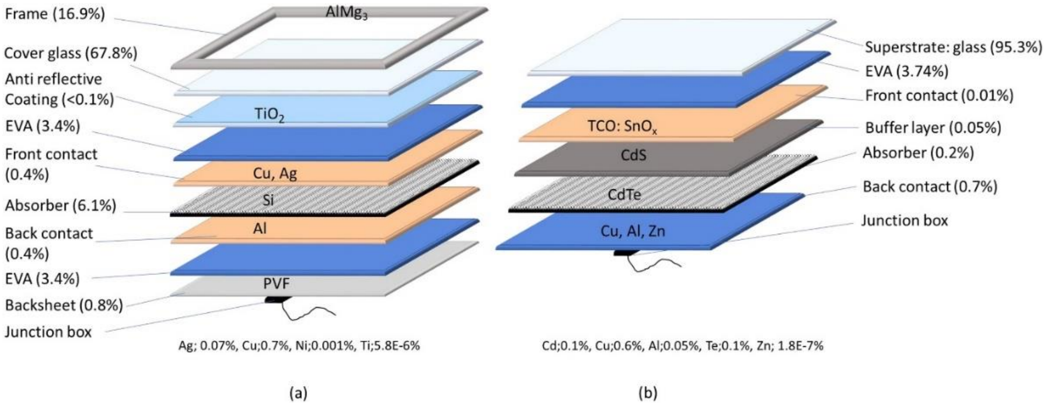

Figure 8: Typical Solar photovoltaic panel structure with percentages of mass compositions (Source: reused from[171]).

The transition towards a low-carbon future and the demand for materials is now visible when the solar market applications account for more than 5% of flat glass volume in Europe, and this can increase to up to 10% in the future[72]. This situation seems to suggest that the demand for glass in the solar industry will far exceed the current supply. Consequently, thousands of new float-glass plants will have to be constructed to meet the solar industry's needs over the following decades[172]. In fact, the high demand for glass in solar PV applications has caused shortages of glass, rising costs, and delaying production of new panels, affecting China's plans to accelerate its shift to a clean power transition[173]. As a result, prices for glass for photovoltaic panels have risen 71% since July 2020, while manufacturers are struggling to produce float glass at a pace to keep more than a week's worth of sales in inventory[174]. Certainly, these dynamics illustrate how glass production comes with high costs in terms of energy requirements, pollution generation, waste disposal[175], economic and environmental costs[176] and materials' scarcity.

Regarding PV's production phase, the environmental impacts are largely due to the raw materials used for the PV cells. For instance, in terms of global warming potential (GWP), polyvinyl fluoride film, silicon, and solar glass account for 45% of the total impact[177]. A similar trend is found for acidification potential, where the usage of raw materials are the GWP's main contributors; silicon being the biggest, followed by polyvinyl fluoride film and solar glass at last[177]. Therefore, although it is true that while PV installations do not emit waste products during operation, augmented installed capacity means increasing PV waste streams in future decades. However, what remains disquieting is that there is no universally employed recycling process for waste PV installations to date[178]. This issue remains vital when by mass, the primary material in PV modules is glass, for every ton (1000 kg) of end-of-life panels (EoL) panels, 686 kg in glass is recoverable and 14 kg is not as it is contaminated and will need to be landfilled[179]. Based on this premise, striking approximations found that 14 million tonnes of waste glass were sent to landfill disposal sites in the European Union in 2007.[72] Other studies estimate that the cumulative mass of EoL PV modules is projected to reach a total 8 million tonnes globally by 2030 and by 2050, the cumulative mass is projected to reach 80 million tonnes[180]. One meta-analysis of global externalities projected that solar PV systems generated a mean of about 5.4 cents/kWh of damages; if one monetizers these damages across the world's annual solar PV generation of about 592 TWh in 2018, solar PV's hidden social and environmental costs could surpass $31.97 billion [181].

Within solar PVs, glass is the material with higher recycling rates, with varying results ranging from 59%[182] to 98%[183]of recovery ratios. However, glass recovered from PV often gets contaminated with Iron (Fe) —due to the shredding recycling process involved — consequently, it cannot be considered as a low-Fe (i.e., high value) glass product[184]. This low profitability has negatively affected investment in the treatment and collection of PV waste [185]. However, alternatives for contaminated glass exist. For instance, downsided glass can turn into fibreglass through a multistep process where the modules are first reduced in size, then glass and laminate are mechanically separated, and the semiconductor is removed by dissolving in acid and peroxide. Research indicates that implementing this approach achieves 90% recycling of glass and 95% of the semiconductors[178]. First Solar, a leading PV recycler, utilises a similar method, where they first separate the semiconductor material from the glass to prevent glass contamination. This strategy not only ensures recovery of a greater percentage of the total system's mass but also reduces abiotic resource depletion and removes potentially harmful substances (e.g., compounds of Cd, Se, and Pb)[186].

Another promising method involves recovering glass without any destructive process using hot-knife/cutter blades (for further information, see: European Union's Resource Efficiency Initiative)[187]. To find a solution to this problematic issue, Heath *et al*. identify three relevant steps for recycling PVs: (1) subsequent purification and separation of the silicon wafer and speciality metals (for example, copper, tin, lead and silver) through electrical and chemical techniques; (2) the mechanical removal of the frame and junction box; and (3) removal of the encapsulant to separate the silicon and glass the wafer through either mechanical, chemical, thermal or processes[169].

5.5.2 Glass in wind turbines

It is often the case that wind turbines produce no direct $C0_2$ emissions when operating; nevertheless, the environmental impacts of their manufacturing process, installation, and EoL stages do. Wind power requires an enormous foundation and long blades built on a high tower to capture and convert wind energy into electricity[188]. To put this in numbers, the weight of one V100-2.6 MW Vestas wind turbine can be up to 259 tons, in addition to approximately 1041 tons of foundation required for its erection[189]. Given that turbines reach the end of their operational life in 20-25 years[190], and that wind power will continue growing[191], we make an urgent call for improvements in resource efficiency to maximise their sustainability and mitigate environmental impacts through their EoL stages.

The link between wind turbines and glass is via glass fibre-reinforced plastics (GFRP) composites (see **Figure 9** indicating annual use of GFRP composites in wind turbine blades). GFRP composites represent most of the blade material composition (60–70% reinforcing fibres and 30–40% resin by weight.)[192] The fatigue resistance of GFRP composites is vital to preserve the structural integrity of the turbine blade and to enhance the reliability of the turbine operation.[3] Despite the benefits provided by wind turbines, the EoL of its rotor blades poses challenges related to waste management for two main reasons. First, treatment options for the installed GFRP are still at a development stage. And second, material-specific characteristics and technical aspects require different treatment of GFRP.[193] In regards to wind turbines EoL, technology for its recycling process exists; however, recycling this material results in low-quality fibresglass[193]. The problem relies on fibreglass containing cross-linked thermoset polymers in their matrices, which cannot be re-molded or re-melted[192]. Thus, their potential to be reused and avoid waste prevention is limited to wind turbines only[194].

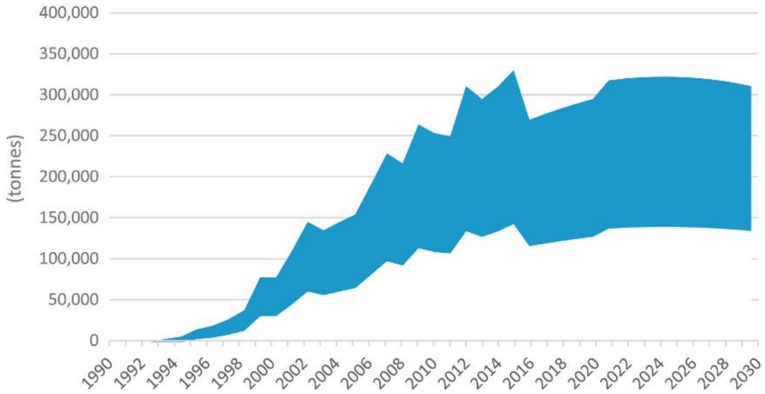

Figure 9: Annual use of GFRP composites in wind turbine blades. (Source: reproduced from[192])

In our review, we found promising methods for wind turbines' EoL. One alternative encompasses the incineration of turbine blade waste in cement kilns to produce the energy required for cement production while also providing vital cement ingredients (to see the complete process see: Tota-Maharaj and McMahon)[195]. Another strategy involves the mechanical separation of the composite components so that the fibresglass and fillers can be used to substitute some of the raw materials often used for manufacturing cement[85]. IRENA indicates a different approach through 'The Dreamwind' project. They suggest separating the glass from the plastic fibres by heating them to 600 °C. Once the separated glass is cleaned, then it could be reused for new fiberglass components for turbines[196].

5.6 Glass in packaging

Because it is odourless and chemically inert to practically all food products, glass has several advantages for food-packaging applications[197]. Since it is impermeable to gases and vapours, glass can maintain products' freshness for an extended time without compromising taste or flavour. Moreover, glass does not deform, and it is suitable for sterilization and cleaning processes[198]. The ability to withstand high processing temperatures makes glass useful for heat sterilization of both low- acid and high-acid foods[197]. Finally, glass has a double potential in terms of container recycling. First, a glass bottle can be refilled up to 50 times before it is recycled as waste glass and then fed back into the production process. And second, glass can be melted down any number of times without compromising quality[199]. Due to these characteristics, it is unsurprising that glass packaging accounts for 24% of total beverage packaging and 40% of total food packaging[49].

The relevance of glass becomes more evident when considering that 62% of the European glass packaging market is held by the food, cider and beer markets. From these three, the largest user of glass packaging is beer which represented about 22.7% of the total glass packs used by European countries in 2018[56]. Outside beverages, and within the food chain, glass packaging accounts for the 40% of total world packaging production[49], making glass the most used material for packaging foods[59]. The preference for glass over other materials becomes more tangible after comparing it with plastic packaging since glass offers more comprehensive benefits in terms of survival of probiotic cultures owing to its extremely low oxygen permeability[200]. However, glass is not only more valued due to its physical properties, but also, consumers prefer glass packaging because of its weight and firmness compared to plastics[198]. Overall, from a consumers' perspective, glass seems superior to other packaging materials[201].

Regardless of users' preferences and benefits, glass production for packaging is one of the major contributors in terms of natural resource use and energy consumption[202] for two reasons. First, glass production is an energy intensive industry, and second, due to the environmental costs of transport[197]. Our review found many studies suggesting that the bottling stage and weight glass are the main contributors to GHG emissions in the beverage industries. For instance, when it comes to wine production, 30% of the energy consumed goes to the packaging and bottling stages[203]. Another study calculated that the wine supply chain in Finland caused 88,668 tons of CO_2e in 2017, where glass bottling caused 72% of these emissions[204]. These results align with other studies that indicate that the most significant opportunities to reduce environmental impacts from wine production are at the bottling stage[205].

Similarly, Heineken found that 53% of the emissions of a bottle of beer are related to the glass bottle itself[206]. Others estimate that 1L of beer packaged in glass bottles consumes 17.5 MJ of primary energy and generates 842 g of CO_2 eq emissions compared to aluminium packaging that requires 11.3 MJ of primary energy, and emits 574 g of CO_2 eq [207]. These results, again, suggest that production of raw materials is the main hot spot in the life cycle of beers. This is not limited to the beverages sector but also to legumes, since the packaging phase represent the main environmental hot-spot for global environmental effects[208].

6. Approaches and technologies for glass decarbonization

Sticking with our sociotechnical approach, this section describes 10 different technological innovations, practices, and legislation that can help decarbonize the glass industry, with an overview offered in **Figure 11**. These nine approaches encompass CCUS, batch pre-heating, waste heat recovery, biofuels, electrification, hydrogen, waste glass and recycling, and other innovations. Later in this section, we present 31 technological advancements and processes (**see Table 6**) that can help transition the glass industry towards a low carbon future.

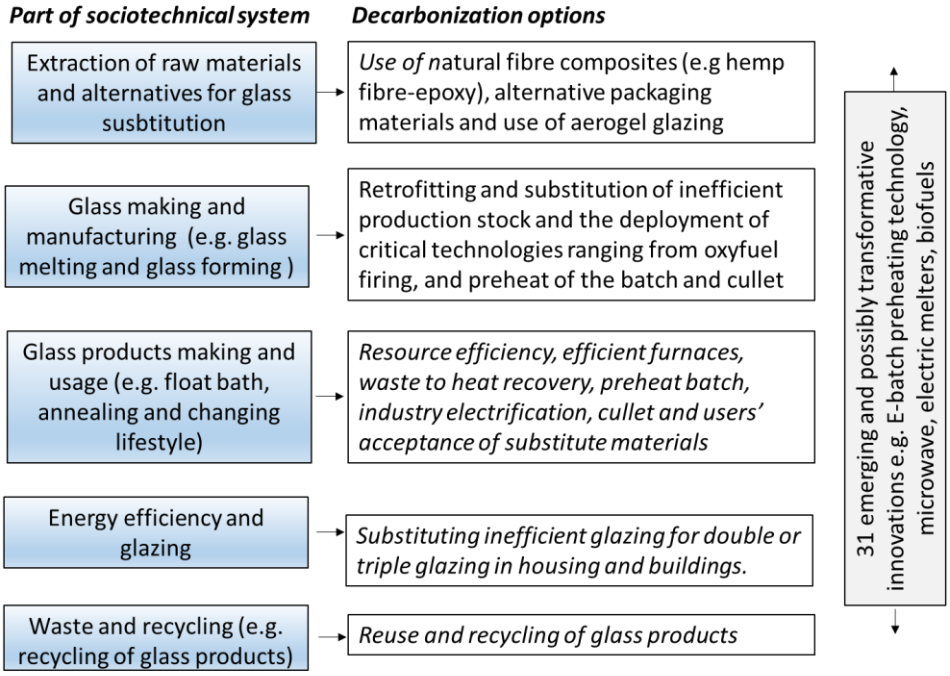

Figure 10: Sociotechnical options for decarbonizing the glass system. (Source: authors)

The glass industry has strived for a reduction in energy demand since the 19th century[13]. This necessity may become apparent when considering that the glass industry spent over $100 billion to power its manufacturing plants in the USA[209]. In Europe, efforts to transition to a low-carbon future have been made; for instance, the glass industry claims to invest each year €610 million on decarbonization through upgrading the energy efficiency of their plants[18]. Moreover, research indicates that almost all float glass manufacturing installations in Europe are certified with ISO14001 and/or EMAS, the EU Eco-Management Audit Scheme[20].

However, such efforts may not be enough since transitioning to a low carbon future will require interventions on both the demand and supply sides. On the latter, measures include delivering equivalent services with less material, minimised material waste, substituting low-carbon for high-carbon materials, and further promoting a circular economy. Rissman and colleagues argue that even the deployment of cutting-edge-low-carbon technologies will not be enough to meet our carbon targets if we do not implement measures to reduce material demand while delivering equivalent or better services[210]. Regarding the supply-side, mitigating emissions will depend on retrofitting and substituting inefficient production stock and the deployment of critical technologies ranging from oxyfuel firing and preheat of the batch and cullet[4] to carbon capture and utilisation (CCU), industry electrification, biomass, and further advancements in hydrogen[211] [212] [213]. It is worth noting that not all technologies are a good fit to mitigate emissions from the glass industry. However, what seems clear is that both sides, demand, and supply, will require public-private sector cooperation to develop and implement effective policy packages and voluntary actions able to stimulate substantial innovation [29] [214] [215].

6.1 CCS & CCUS

This literature review identified that for some the deployment of these technologies is unavoidable due to the size and GHG dilution of a typical glass installation[70] [216] [217]. Others perceived CCS as a complementary technique to mitigate GHG emissions. For instance, adding a sequestration system to the oxy-fuel combustion process can reduce emissions by a total of 75%[55]. Another option to mitigate emissions is through bio-energy with carbon capture and storage (BECCS)[218]. This approach could bring better results compared to other technologies (e.g., natural gas or hydrogen fuels) since biofuels typically burn with a more radiant flame, have lower calorific value content per kg, and contain higher moisture content[219], characteristics that are essential while manufacturing glass. On the same line, adding CCS to a Waste-to-Energy using cullet has the potential not only to deliver zero waste but it could even be a source for negative emissions[220]. Due to the high temperatures required for glass production, electrifying this industry is challenging. Thus, CCUS is a relevant option for direct process emissions that cannot be otherwise abated through electrification.

Regardless of how promising CCS and CCUS are, there are still some barriers to overcome. First and foremost, since its deployment still represents high costs and due to the low carbon trading price, CCS investments are chiefly supported through subsidies, which results in high burdens to the government[221]. Others note that the main barriers for CCS deployment are related to separation technology, CO_2 transport technique, and the storage site[222], taking into consideration that most of the glass manufacturers are characterized by being small disseminated units primarily located in brownfields, capturing emissions systems do not seem like a feasible investment option for these manufacturers[223].

6.2 Batch preheating

Our review found that batch preheating could be an optimal mean to mitigate emissions from the glass industry. This process consists of capturing and passing hot exhaust gases from the back end of regenerators through cullet or batch to recapture sensible heat and re-absorb dust and SO_x[4]. This is a mature technology, relatively easy to install[55] and extensively applied in the glass industry[223]. With CAPEX and OPEX costs estimated at €1.5 million and €120,000 respectively for a 350 tonne/day cross-fired regenerator furnace container glass furnace[17] batch preheating is one of the BAT leading to reducing CO_2 emissions, increasing production rates and high energy savings [43] [224].

Batch preheating systems can be installed at any existing glass melting furnace with a cullet ratio of more than 50%[43]. However, other studies report it needs no more than 30-40% cullet to deliver optimal results[223]. For instance, applying a 50:50 mix of batch and cullet and then preheating at 500ºC reduces fuel consumption associated with melting by 8-12%[225]. Another study conducted by IIASA estimates that net fuel savings are estimated at 0.76 GJ/ton if the cullet's percentage is at least 50-60%[226]. Berkeeens found that energy savings ranged from 12–20%[227]. This aligns with other results that indicate that batch preheating can reach energy savings of up 15%[228]. Chan and team, using this technique, reduced 7% of CO_2 in comparison to the conventional glass manufacturing process. They calculated that if this approach is employed across the EU, the glass industry could mitigate up to 1,256 kT of CO_2 emissions throughout the region[55]. Finally, HotoxyGlass --an EU program-- achieved more than 19% of energy savings and mitigated 5.5% of CO_2 emissions by using preheated oxygen instead of air mixed with natural gas for powering float glass furnaces. Other environmental benefits that were found included reductions in NO_x, SO_x and dust[229].

However, batch-preheating comes with some drawbacks. For instance, it is often capital-intensive, and sometimes, its installation requires equipment on the same size scale as the melter itself[230]. Moreover, if cullet exceeds the mix, other problems could emerge, such as dust carry-over and clogging problems[224]. Finally, although this approach certainly carries energy savings, other innovations such as electric heating and insulation of the smelter demand less waste heat for batch preheating[55].

6.3 Waste heat recovery

Our analysis found that waste heat recovery was yet another viable option to mitigate emissions from the glass industry. This technique deals with the advanced utilization of the furnace exhaust gases, which typically have a heat content that reflects 25–30% of the furnace energy input[43]. Waste heat recovery can take different forms: heat, power, and fuel recovery[231]. Different heat recuperation strategies exist; the most prominent include: exploit the heat for thermal uses (e.g., generating process steam, preheating raw materials and fuel, or for auxiliary systems and heating rooms), control the heat for external thermal uses, and generate electricity that is often consumed within the plant through technologies such as Organic Rankine Cycle (ORC)[22]. Waste heat recovery has gained attention in energy-intensive industrial processes since these represent the most significant potential waste heat source[25] [232]. Therefore, this approach can reduce industrial energy demand, increase energy efficiency, and improve ambient air quality by reducing industrial pollution and greenhouse gas emissions[233] [79]. Waste heat recovery installations already operating across the EU exist, such as the 0.5 MWe ORC generator at the OI Glass container plant in Villotta di Chions Italy and the Siemens waste heat recovery systems based in Germany that allows a 60 % of electricity produced by own waste heat flow[234]. Capex and OPEX costs for this technology are estimated at €1.67 million and €33,500 p.a. respectively for a 300 tonne/day container glass furnace (end fired) with heat extracted after Electro-static Precipitator[107].

Li and colleagues illustrate the potential of this technique to mitigate emissions. Their study shows that installing a waste heat recovery power generation system on the glass line can reach savings of 12,400 tons of coal equivalent and a reduction of 0.84 MJ energy consumption per kilogram glass. Overall, this technique's potential to mitigate SO_2, NOx, CO_2 and dust emissions are 28,500 tons, 83 tons, 33 tons and 79 tons, respectively[25]. Others approach waste-heat-recovery through an ORC. This technology can generate energy savings and enhance thermal energy efficiency by using low- and medium-grade waste heat[235]. Schmitz *et al*. indicate that ORC could be a good investment only if the levelized cost of electricity is lower than the grid electricity price, making this technology extremely promising for the glass industry but in limited contexts[77]. With this in mind, Villar and colleagues conclude that waste heat recovery technologies are vital to reduce energy use and GHG emissions in the glass industry in a medium- and long-term approach[236].

6.4 Biofuels

Although we did not find many studies using biofuels to decarbonize the glass industry, some studies indicate a promising way forward. Biofuels are fuels derived from biomass and, if combined with carbon capture technologies, provide an opportunity for net-negative CO_2 emissions (i.e., BECCS) for glass manufacturing processes[219]. For instance, biofuels, such as biodiesel, can offer adequate high-temperature heat upon combustion, making these energy sources ideal for the glass manufacturing process[218]. However, it is worth noting that biofuels often come with a high carbon footprint and are more expensive than fossil fuels. It is in this context that Napp *et al*.,[237] suggest that biomass and waste should be substituted through biomass and waste with the implementation of appropriate policy mechanisms such as a carbon price, subsidies, and regulations.

This technology's potential is illustrated by Chan *et al*. They suggest that using biomethane for the smelting process, manufacturers could bring their emissions to net-zero since biomethane's lifecycle would absorb the emitted CO_2 during production[55]. Deng *et al*., identified biomass ash as a promising alternative to reduce energy and mitigate emissions in the glass industry. Particularly, they note that biomass ashes could be used as a replacement for sand and limestone in industrial glass. Their study concludes that biomass ashes contain several components with value for commercial glass production[238]. Research conducted by The Department for Business, Energy and Industrial Strategy (BEIS) suggests that the UK possesses biofuel capacity to supply the entire glass sector. This approach, as noted, could be enhanced with the application of CCUS[219]. The study indicates that biofuels offer a lower cost to decarbonise existing glass furnaces, with less investment required for new infrastructure in comparison to large-scale electric melting. An example of this technique was developed by Encirc, the glass container manufacturing company. They attempt to use biofuels in furnaces, switch from heavy fuels to gas and use 96% of recycled glass, while processing over 300 tonnes of glass per day[239].

Despite the potential of biofuels, there are some barriers to overcome. Leaving aside the cost, there are issues pertaining to quality requirements and distribution challenges, affecting, in turn, the availability of biofuels that the glass industry would require. For example, Glass for Europe suggests that even if the current annual production of biomethane (19352 GWh) , were to be entirely absorbed by the flat glass sector's plants, it would still be insufficient to meet the energy needs of today's 52 EU-based float glass lines[93].

6.5 Electrification

This literature review identified that electrifying the glass industry is a promising method to mitigate emissions. Some researchers even indicate that electric melting is the most energy-efficient method for furnaces and to achieve deep emission reductions in the glass industry[19] [240]. However, the technology is commercially available only at small scales[241], and it remains unclear if electric melting technology can be up-scaled to more extensive production processes (i.e.,>200 tonnes per day)[211]. This is because the flat glass melting requires extremely high temperatures – more than 1,600 degrees – and the furnaces are quite large and constantly operating. Consequently, reaching 100% electric melting in the glass industry has not been possible yet[108], although some expect that all-electric systems could be available for commercial implementation post-2030[33].

The capital costs for this approach are estimated to be around €1.67 million for a 300 tonne/day container glass furnace (end fired) with heat extracted after Electro-static Precipitator[225]. Current fuel-based heating is relatively inefficient compared to what potentially could be achieved with electric heating. For instance, using electric furnaces result in lower process energy losses and lower emissions of NO_x compared to traditional fossil fuel heating at 1.1MWh/ton net energy use is around 35% lower[242]. Other studies have found that using an all-electric system is 31% more efficient than conventional manufacturing methods and can save 5,561 kT of CO_2 in the EU glass industry. Glass Alliance Europe has likewise identified that an all-electric system could reduce energy inputs by 30%[223]. Lechtenböhmer et a. indicates that a conversion to electric ovens results in an overall increase in the final energy efficiency of glass production of about 68% from approximately 2.1 MWh/ton to 0.85 MWh/ton[243].

Further CO_2 emissions can be mitigated as the electricity grid incorporates more low-carbon energy sources, potentially reaching up to 75% emissions reduction[55].

In this review, we also identified some critical barriers to electrifying the glass industry. For instance, Lechtenböhmer and colleagues estimate that electricity demand could increase by 170% from full electrification [243]. As a consequence, not only the local grid would need to be reinforced to provide the required power [55] but also, peak demand could increase energy costs[80]. Indeed, the greatest barrier to electrification related to the economics of electric melting are those related to the higher costs of electricity compared to other sources [240] [244]. As already noted, Glass for Europe suggests that technology for electric melting is not yet compatible with high-temperature glass furnaces with a production of over 200 tonnes a day (i.e., three times below the production volume of an average float glass plant)[93]. The same study warns that another technical challenge is related to the fact that electric melting is not suitable for high cullet ratios since it is difficult to maintain down the superstructure temperatures. This hurts the sustainable aspects of using more recycled glass.

6.6 Hydrogen

Hydrogen is a clean-burning molecule that could become a replacement for fossil fuels in hard-to-abate sectors of the economy[245]. It is an energy carrier that holds great potential for decarbonizing many industrial sectors and applications, with high temperature heating being one of the most prominent attributes [246].

Our review found contrasting opinions on the use of hydrogen for glass decarbonization. On the one hand, some claim that glass manufacturing's temperature requirements favour the utilization of hydrogen [247] [248], for instance, by retrofitting glass furnaces to use hydrogen instead of natural gas. Alternatively, oxyfuel burners could combust the hydrogen with pure oxygen instead of using air to avoid NO_x formation [241]. On the other hand, other studies claim that hydrogen poses technical challenges since it has lower volumetric energy content and produces a flame with lower radiation heat transfer than natural gas. These factors make hydrogen a much less efficient option when compared to natural glass[219] [223] [108]. Therefore, more technology development and demonstration work would be needed to make hydrogen a useful fuel for glass manufacturing[219]. Nevertheless, researchers are exploring how hydrogen can match the same heating profile as natural gas for glass furnaces. For instance, the Flamatec division of Glass Service, through extensive computer simulation and engineering work, developed a high-temperature combustion facility operating with hydrogen[249]. Regardless of this progress, barriers remain regarding a lack of effective production-scale technologies.[219]

6.7 Innovations in heating and melting

Oxy-fuel furnaces are another relevant technology to mitigate emissions from the glass industry. This technology uses oxygen instead of air for combustion, reducing the amount of inert nitrogen to be transported or heated[241]. In comparison to a conventional furnace, oxy-fuel combustion reduces the amount of flue gases by 60–70% [33] and mitigates energy losses from 25-35% compared to a furnace without additional heat recovery[11]. Other studies indicate that fuel savings range from 5-20% concerning large, efficient regenerative furnaces[225]. For these reasons, Levine, and colleagues suggest that **"***conversion from air-gas to oxy-gas firing is the single most promising means to reduce energy use* [230]*."*

Microwave heating is another promising way to design cleaner, faster, and economically viable synthesis glass methods[250]. An outstanding characteristic of this approach is that microwaving enables fast-uniform heating processes while removing volatile elements (moisture, binders, etc.) and reducing the thermal stresses in the heated material[251]. For instance, some studies found that microwave-assisted technology can reduce process time by 34% and energy consumption by 25 % percent[247]. Dorn *et al.*, demonstrates that overall energy consumption can be reduced by about 50% using microwave technology even when compared to a full-scale conventional plant[40]. Other studies not only emphasize how microwave technologies cut down carbon emissions of glass material processing but also how this technique can significantly accelerate the heating process[252] [253].

Other studies focused on plasma melting as a promising technique. Plasma owns a number of properties that make it easy to melt raw glass powders with minimum ecological risk and at a rapid pace; thus, reducing the use of fossil fuels and mitigating GHGs[78] [254] [255]. However, plasma processes have some downsides, such as electricity utilization as input and high installation costs[256]. Other studies mentioned practices such as Praxair's technology, where batch–cullet is fed at the top of the preheater and "rains" through a heat exchanger[4]. Another alternative is producing batch using diatomite, which allows the manufacture of foam glass with stable physical-chemical characteristics at a lower cost and increased energy efficiency than traditional foam-glass manufacturing technologies[257]. Finally, flexible fuelled furnaces seem to be another promising technique, although little research has been conducted on this area. BEIS suggests that this technique has the advantage of allowing dynamic fuel switching. For example, a furnace could dynamically switch from electric to biofuels to support future smart load balancing networks. This, in turn, provides the ability to increase glass pull rates while enabling demand-side response options that support overall electricity system efficiency and reduce fuel supply disruption risks[219].

6.8 Glass waste and recycling

In this review, we found different mechanisms to minimise the environmental impacts from the glass packaging industry. For instance, studies [205] [207] [208] [258] [259] [260] suggest that reducing the weight of containers is the best approach to mitigate environmental impacts, not only due to material efficiency but also because lightweight packaging will make transportation over long distances more energy efficient. In fact, a weight reduction of the glass bottle by 24% could avoid 11% of the average GHG emissions per bottle of wine[204], while a 20% reduction can mitigate emissions by 8% [261]. Industries, nevertheless, seem to be paying attention to this thought, since on average, glass bottle weight has been reduced by around 25% since 1984[262].

Others suggest advanced packaging options, for instance, replacing glass bottles by composite materials of recycled cardboard and plastics, since these can save significant amounts of material and achieve the same level of protection[260]. Regarding beer packaging, research suggests the use of canned beers to mitigate environmental impacts since they have lower impacts than glass bottles and aluminium packaging[207]. Another study compared glass food containers to plastics, and the results show that glass containers have 12%–64% higher environmental impacts than plastic and should have about 3.5 times greater lifespan to match the environmental footprint of plastic containers. Thus, consumers should aim to extend the lifetime of glass food containers, as they have higher environmental impacts than plastics[263]. There are other products that represent more sustainable options when compared to glass, most notably are carton-based containers and PET packaging options[258] [259] [264].

Many studies emphasise the use of cullet and bottle reuse to mitigate emissions [198] [207] [208]. For example, every 10 % increase in the number of recycled glass containers can reduce GWP by about 3 % in the EU and UK[207]. Promoting circularity in the glass industry remains a vital priority within the EU. Since glass is 100% recyclable, 70% of all glass bottles are collected for recycling annually, 90% of the glass containers 'close the loop' --as they go back into a bottle-to-bottle production system-- and 1 tonne of recycled glass saves 1.2 tons of virgin raw materials and avoids 60% of CO_2 emissions[265 266]. The EU states that most promising pathway toward circularity within the glass industry is to focus on products reuse rather than recycling. Given that reusable glass bottles require a thicker design, glass bottles can be washed and refilled multiple times before needing to be recycled, eliminating the need to produce new raw materials for glass production[267] as **Figure 10** illustrates. To maximize the approach and mitigate impacts from glass containers, Souder and colleagues propose further expanding bottle deposit systems and redesigned them towards localized glass bottle reuse/refill systems, with unusable bottles directed towards glass recycling[268].

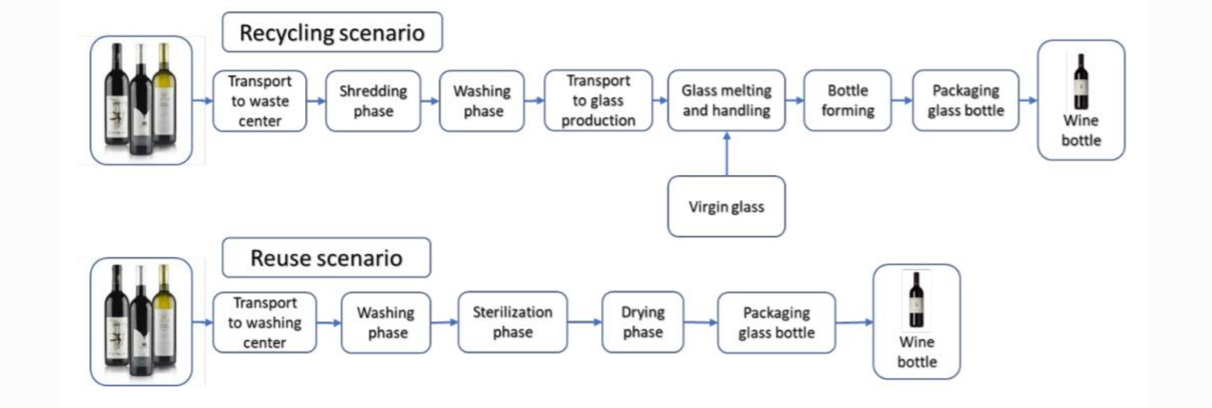

Figure 11: Recycling and reuse scenarios for glass wine bottles (Source: figure retrieved from[203]).

At a more general level, other recycling activities can further lower the carbon and environmental footprint of glass. The literature often distinguishes three different types of glass recycling: product recycling, material recycling, and feedstock recycling[151]. Over the past decades, glass recycling has gained more relevance in the glass-making process. For instance, float glass usually contains at least 20% cullet, representing more than 5 million tonnes of recycled glass used annually in Europe’s float glass operations[20]. In other cases, cullet accounts for up to 95% of the batch for specific types of products. Cullet comes in two forms: internal cullet (glass rejects from production that is reintroduced into the furnace that produced it), or external cullet (coming from collection banks or processing plants)[22]. In glass recycling, different types of glass go through different recycling processes and are melted at different temperatures. However, as Francheti [269] explains and as presented in **Figure 12,** there are some similarities in this process. First, at the recycling facility, the glass is crushed. Cullet then goes through various processes to remove non-glass items. Strong magnets remove ferrous metal, and air jets separate metal pieces from the cullet. Once the cullet is ready to be turned into new glass, it goes into a furnace where it melts at a temperature of 1,500°C/2,700°F. This heat melts the cullet and turns it into a liquid called molten glass. The molten glass is shaped into moulds to become glass products like bottles, and jars.

Belgium, Norway, Germany, and Sweden are the top EU countries at recycling glass with a rate of more than 85%[270]. However, glass recycling practices still need to advance in the rest of the world, since glass is one of the major waste products in all urban areas. For instance, data indicates that Europe generated ca. 17 million tons of glass[120]. In 2018, glass generation in all products was 12.3 million tons in the USA, which represented 4.2 % of all municipal solid waste (MSW) generation. In the USA, the number of recycled glass containers was 3.1 million tons during the same year, having a recycling rate of 31.3%[271]. In Australia, over 1.3 million tons of packaging glass is consumed per annum. From this, only about 40% of the used glass in this pool is recovered[269]. In South Africa, 150,000 and 300,000 metric tonnes of waste glass are generated, and only 20,000–60,000 tons of it is recycled annually[272]. Portugal and Hon Kong are also relevant, with the first generating approximately 425,000 tons of waste glass, and only 192,000 tons have been recycled. In Hong Kong, about 373 tons of waste glass were generated daily in 2010[273]. Given these examples; it may not be surprising that the estimated volume of landfilled glass worldwide is about 200 million tons per year with a very low recycling rate[2]. It is under this context that the European Commission proposed new targets for municipal waste with reuse and recycling of glass contained in packaging waste set at 85%[274].

The benefits from recycling glass are wide and varied, ranging from the conservation of natural resources, reduced landfill space, diminished need for mining raw materials, reduced air and water pollution, and the creation of new jobs[178]. For instance, as cullet is a previously melted glass, the energy needed to melt it again is lower. Therefore, increased cullet use leads to decreased energy consumption for melting a batch, requiring between 70%-75 less energy[275]. The volume of gases released from the batch is lowered as the amount of other raw materials is reduced (for instance, less carbonates releasing CO_2 from the batch)[22]. Regarding saving materials for flat glass, one tonne of recycled materials results in savings of about 1200 kg of virgin material, 25% of energy savings, and 300kg of CO_2 emissions mitigated (directly associated with the melting process)[276]. Other studies calculate that adequate recycling of all building glass waste, compared to the business-as-usual scenario, could save over 1.2 million tonnes of primary raw materials, mitigate carbon emissions by more than 230,000 tonnes annually and avoid 925,000 tonnes of land-filled waste every year[277].

Recycling glass comes with other benefits. For instance, Maier and Durham estimate that for every ton of recycled glass, 1000 lb (454 kg) of CO_2 is saved from being emitted into the atmosphere[142]. The European Commission further estimates that for every 10% of cullet used in the production process, a producer saves 2-3% of energy compared to using virgin materials[278]. Vossberg *et al*., indicate that recycling container glass instead of landfilling can achieve GHG emissions savings of 37% and energy savings of 27%. Their study concludes that almost 25 times more GHG emissions and six times more energy were avoided by recycling one kilogramme of glass versus one kilogramme of construction and demolition waste[272]. Similar evidence suggests that making new glass from recycled glass reduces the CO_2 emissions and energy use required for producing every new bottle - saving 580kg of carbon dioxide emissions with every tonne of glass re-melted[279]. Beerkens *et al*., indicate that using cullet reduces dust during batching and requires up to 25–30% less energy to melt than an isochemical batch of raw materials[35]. More specifically, in the EU, 74% of container glass is recycled, saving approximately 9 million tonnes of CO_2 every year[223].

Figure 12: The recycling pathway for demolition waste. Source [280]

Despite the number of benefits recycling glass offers, it can also be impractical or expensive when, for instance, waste glass is broken, contaminated, or comes in different colours[281]. Moreover, waste glass must be sorted, cleaned , and then melted to produce glass containers and plates[143]. Another challenge is glass's different chemical compositions. For example, different glass colours have different chemical compositions and material properties, which may be suitable for specific applications but challenging for recycling[142]. Regarding the cleaning process, glass can be contaminated with metallic and non-metallic fragments. In turn, the use of such mixture in new material manufacturing is not optimal since the final products will most likely have poor quality[282]. Other issues go beyond the recycling process itself and include poor regulatory frameworks (e.g. glass collection schemes), lack of infrastructure and commercial imperatives, impacting recovered glass commodity value[283] [284]. These issues may help to corroborate Alani's *et al.* views when they note that "*Currently glass is one of the least recycled materials in a majority of countries*"[119] and another study indicates that "*glass containers from residential and commercial recycling operations have provided a consistently low market value relative to other recovered materials* [285]*.*"

Other perspectives emerge from the position that glass recycling has less to do with any physical properties, but it is closer to political factors and the shifting interactions from markets[286]. The argument is based on the fact that glass recycling is not only challenging but also an energy-intensive practice. This position takes more relevance when others suggest that the recycling processes could be more expensive than building a new product[3]. Other complications emerge when the waste liquid resulting from removing old labels from bottles is categorized as a hazardous substance and has to be disposed of at specific licensed sites. In addition, the re-use of most packaging glass requires high-temperature washing for sterilization[287]. It is perhaps due to these circumstances that currently, the recycling rate of waste glass is meagre. While more than 130 million tons of glass were produced worldwide in 2018, only about 21% of it was recycled[143].

However, these shortfalls are now being addressed. For instance, optical identification using technologies such as digital imaging and spectroscopy to identify contaminated waste glass is now used[288]. Others use microwave-assisted chemical oxidation methods to reduce energy consumption during the recycling of glass fibres[289]. Veolia aims to deliver an “ultra-pure” glass cullet to avoid emitting more than 12,000 tonnes of CO_2 while achieving energy savings of 76,000MWh, compared with traditional methods of manufacturing mineral wool[290]. Other innovative methods consist of utilising processed glass to replace sand as a filter media in water treatment and industrial settings[291]. Others place the responsibility on consumers and suggest that the debate should focus on the desirability of re-using packaging rather than recycling if we want to mitigate emissions and conserve raw materials[292] [268]. Meanwhile, others place the responsibility on the producers and suggest enforcing an Extended Producer Responsibility (EPR) approach, since this strategy could lead to more investment in recycling infrastructure and improving the collection rates for glass while promoting a circular economy[293].

6.9 Energy efficiency and glazing in buildings

Decarbonizing the building sector is a key component of achieving a low-carbon future; therefore, the European Commission requires all new constructions to achieve nearly-zero energy standards by 2020[294]. Besides, all building's renovations should be cost-effective, hence, requiring energy efficient glazing[20]. Glazing in buildings has different forms depending on the building type, the frame material used, location, installation period, etc. Glass, hence, can be grouped into three categories[103] as **Figure 13** illustrates.

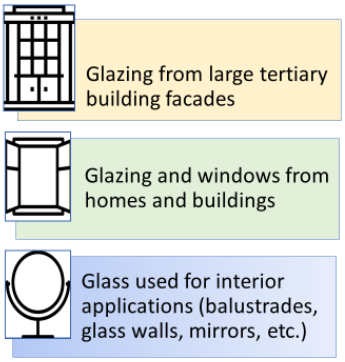

Figure 13: Glass in buildings grouped into three categories. (Source: authors)

Windows are a crucial element for indoor comfort and are critical in terms of the energy consumption of buildings[295]. Therefore, the design and performance of window frames and glazing are essential elements for implementing thermal regulations and contribute to the success of energy renovation policies[296]. Windows are also crucial for the provision of daylight and external viewing, both of which have known positive psychological benefits[297] and help reduce the need for artificial lighting[20].

In terms of energy, efficient glazing and windows possess an enormous capacity to increase building energy performance, reduce emissions and help individuals through energy cost savings[223]. This should take increased relevance given that 85% of the glazed surfaces in

Europe contain inefficient glazing, resulting in up to 60% of the total energy loss of a building coming from inefficient windows[298]. In fact, evidence indicates that savings of more than 100 million tonnes of CO_2 could be achieved annually if EU buildings were fitted with advanced energy-saving glass (e.g., triple glazing)[299]. This represents more than a third of the EU's prior 20% energy saving commitment for 2020. Although not as dramatic as in the EU, the energy lost through today's inefficient window stock accounts for around 30% of building cooling and heating energy consumption in the USA[300]. In Japan, research suggests that by expanding the use of multi-glazing with high insulation properties and other eco glass technologies, it is possible to remove around 68 million tons of CO_2 when renovating existing buildings and 64 million tons for new-buildings[301]. The energy savings are not limited to windows, but mineral insulators such as glass wool can improve the building's efficiency as well as operate as an efficient filter for particulate matters[302]. This material owns several properties that makes it a good absorber of moisture, increasing thermal conductivity and thus, increasing operational energy use[303].

From a life cycle assessment perspective, investing in more efficient windows has net negative lifetime economic and environmental costs. The energy savings rapidly pay back the investment and CO_2 emissions associated with production[71]. For instance, research indicates that for commercial buildings in London, the use of low-emissivity glazing reduces heating and cooling loads by more than 50%, offsetting the increase in energy used to produce the curtain wall[304]. Other studies show that in the EU, the total CO_2 equivalent generated by an energy efficient double glazing unit throughout its life-cycle is offset in only three to ten months when just counting the energy savings realized by single glazing[20].

Regardless of the benefits mentioned above, we should consider that windows also represent a substantial material flow with an approximate consumption of 73.2 million units in 2012 throughout the EU [305] and 49 million units in the USA in 2016[306]. Alternatives for substituting glass through more sustainable options exist, such as aerogel glazing (see, for instance, Jelle's and colleagues work[298]). However, efforts to mitigate emissions ought to persist and should not be limited to technology development alone. But to reduce energy consumption from buildings, we need to advance on other areas, including education and knowledge of producers and consumers and governments' support to help the most vulnerable groups with funding opportunities to retrofit and insulate buildings.

6.10 Emerging technologies and processes for mitigating the environmental impacts of the glass industry

In addition to the technologies and processes identified in the previous sections **Table 6** presents 31 innovative options that mitigate emissions from the glass industry production processes.

Table 6: Thirty different innovations for making glass manufacturing more sustainable. (Source: Authors compiled from [19][28][29][229][238][253][307][308][309][283][310][311][312][313][314][315][316])

Process	Technology	Benefits
Batch preparation	Laser-induced breakdown spectroscopy for improved control of glass feedstocks	Can determine if the batch was constructed correctly to control glass quality. It can also tell if individual batch ingredients are within specifications. Regarding cullet feedstocks, this approach can serve as part of a system to sort cullet by colour and guarantee if it is free of contaminants. This technology achieves 20% reduction in product defects, which could lead to savings for the U.S. glass industry of $220 - $440 million per year. In addition, it could produce energy savings of about $358,000 or 54,000 GJ yearly for a single-furnace glass factory manufacturing 250 tons per day.
	Infrared Sensors	Infrared sensors are capable of isolating minerals, porcelain, and ceramics. Thus, this technology helps in separating glass with different chemistries, like leaded glass or windows, and digital imaging to separate by colour. Energy savings using this technology are estimated at 2-3% through reduction of the rejected rate.
	The X-STREAM Glass	Similar to (IR sensors), this technology sorts cullet by passing it under arrays and separating contaminated fragments away from safe glass with the use of a blast of air. Once the contaminated glass is separated then, the recycling process can continue.
	Using lithium as a fluxing agent	Reduces melting temperatures at equivalent melting energy and cullet input while providing enhanced forming properties and augmented nominal furnace capacity. Research indicates that adding lithium to glass batches can reduce furnace energy consumption by 5-10% while simultaneously mitigating NO_X emissions.
	Reduce batch wetting to a minimum	Water content leads to increments in energy consumption. Thus, wetting ought to be reduced to a minimum. Reliant on the percentage of cullet, reducing moisture content of the batch by one percent will result in fuel savings in the furnace of 0.5%.
	Novel mixers	There are numerous categories of batch mixers (e.g. ribbon, ploughshare, orbiting screw, rotating pan and ring trough mixers). Rotating pan mixers display the least variability in composition in the shortest mixing period. This leads to energy savings in the furnace due to enhanced product quality and more efficient melting.
	Selective batching	Selective batching is a technique that can be used to improve melting efficiency by reducing the chemical reaction of alkaline-earth and alkali carbonates while promoting reactions among the quartz and the fluxes. This approach can reduce melting times by 50% or more and achieve energy savings between 20-33%.
	Grinding	Energy efficiency increases with high feed rates and low rotational speeds. Moreover, grinding for cullet makes easier to remove contaminants. RemCo, for instance, claims to produce 99% clean cullet through this approach.
Batch and Cullet Preheating	Raining Bed Batch and Cullet Preheater	Utilizes a heat exchange system to preheat glass furnace charges with hot flue gasses. Cullet is then put at the top of the preheater and "rains" over the heat exchanger. Using this method allows recovery of 527 MJ per ton of glass produced, plus 25% reduction in fuel and oxygen in oxyfuel glass furnaces. A key benefit is regarding the payback period which could be in less than four years
	Hyper spectral imaging technologies	Operates by combining a spectrograph with a digital camera, measuring the reflectance spectra of mixed cullet in the mid and near infrared range. In turn, this approach offers benefits by sensing any difference among glass colour types.

	Flue-gas treatment with dry sodium bicarbonate and chemical valorisation of gas treatment residues	Applies to the desulphurisation of waste gases from glass melting furnaces. In this process the solid residue is separated from the flue-gases by filtration systems. This technology allows that the solid residue is recycled in the melting furnace and thus, used in the batch formulation. This strategy achieves high removal efficiencies of SO_X emissions and the opportunity to treat and reuse the solid residue generated by the scrubbing system.
	E-Batch Preheating Technology	Utilized for preheating cullet and batch using the waste heat from furnace exhaust gases. This technology is unique because it is specifically designed to operate with oxy-fuel-fired furnaces and incorporates exhaust gas cleaning to the strictest regulatory levels. Savings range from 15-25% in furnace energy requirements. Moreover, it provides the ability to handle any mixture ratio of cullet and batch.
	Oscillating Combustion	Forces the oscillation of the burner fuel to create successive, fuel-lean and fuel-rich zones within the flame. Fuels savings implementing this approach vary from 2%-27%, with a reduction in energy consumption of 16% to 32% and efficiency improvement of over 6%. This approach also mitigates NOx emissions by 30%-50%.
Technologies for Glass Melting	High speed convection	Transfers more of the heat by convection (over 50%) using a lengthwise system of heating elements in the furnace. Tamglass, a Finnish developer, claims production increases of as much as 40%, achieving reductions in energy costs while increasing process reliability.
	Segmented Melter	Melts batches in an electric melter, afterwards the cullet is added in a separate oxy-fuel fired melter. This technology achieves 25% improvement in thermal efficiency. However, other benefits include: reduce costs on materials, the facility to do local maintenances in each segment and lower the tank volume. Moreover, if the batch melting employs an electric furnace, on-site emissions can be removed in the high temperature stage of melting
	Plasma Melter	Well-suited to glass batch processes that require high melting temperatures and low production volume. Improvement in energy intensity through this approach vary from 50%-70%. The downside is that plasma melters might be expensive with estimated costs of $500,000 - $700,000 for a 500 lb/hour facility.
	Air bottoming cycle	Waste heat from a gas turbine is used to preheat the combustion air of the glass furnace. The average energy savings are estimated at 10% with an estimated payback period of 3-4 years.
	Submerged combustion melting (SCM)	Fires fuel and oxidants into and under the melting mixture of a furnace. During the combustion SCM maximizes and augments the melting rate while the heat transfer reduces the residence time of the melt in the tank. Energy savings are calculated at 5%-20% compared to a state-of-the-art oxy-fuel furnace and capital costs could be cut by 55%-80%. The average energy savings were estimated at 10% with an estimated payback period of 3 to 4 years.
	In-flight melter	Disperses raw material in a melter so that the raw material is in full contact with a flame, allowing rapid heat transfer. This technique removes gases when the raw material is injected, preventing bubbles and allowing the melting to occur quicker. The results is faster melting time, saving energy and increasing yield.
	Oxygen transport membranes	Separates O_2 through a non-galvanic electrochemical mechanism occurring within an O_2-ion transport dense membrane. The technique achieves lower specific energy consumption and higher energy density compared to conventional glass melting furnaces.
	Premix burners	Premix burner are made of three key components, a nozzle, the burner head, and a feeder to feed the mixture of air and gas. The use of this technology allows air and gas to mix at some point upstream from the burner ports by an inspirator mixer or a mechanical mixer. Implementing premix burners can potentially deliver energy savings of about 11%.

	HOTOXYGLASS (EU funded project)	Uses pure oxygen instead of air as oxidizer for environment-friendly effects and fuel-efficient means for flat glass production. In addition, this method includes a new heat recovery technology to make oxy fuel combustion more efficient. The results have shown up to 35% on SOx reduction, compared to a standard air fuel operation.
	Glas Flox ® flameless burner	'Flox' refers to a flameless burner where the combustion of gas and air takes place. The operating principle is based on internal recirculation of combustion gases, that are 'sucked' in the flames by the low pressure at the burner outlet. The combustion chamber can reach high and homogenous temperatures which in turn, improves energy transfer to the melting glass. This system not only mitigates CO_2 emissions, but also mitigates 50% of NOx emissions in comparison compared to traditional burners.
	The Optimelt system	Utilises waste heat as a method to produce syngas. This system's main benefits are related with improvements in fuel efficiency and energy savings.
	Microwave heating	Can cut by half the energy intensity of conventional furnaces (a more detailed explanation see **section 6.7**)
	Porous burners	Allows combustion to take place within a porous medium, (e.g., a ceramic matrix with large pores). Porous burners enables enhanced control of the reaction process and are also less sensitive to variations in fuel quality. The benefits of this technology are energy savings, reduction of emissions and improved glass quality.
	'Furnace for the Future' (F4F) (not implemented yet)	Replaces up to 80% of the natural gas with renewable electricity combined and other sources of energy such as hydrogen or biogas. The F4F technology will cut direct furnace CO_2 emissions by 60%, and 50% from the whole installation.
	Image-based control of glass melting furnaces	Uses advances in imaging and modeling commercialized by Siemens SIGLAS and is estimated to reduce energy use by 2%-8%.
	Oxy-fuel fired forehearths	Operates in a similar way to oxy-fuel firing in furnaces, where use of oxygen reduces fuel use and emissions, eliminating the need for additional heat energy and improving heat transfer through hotter flames. It also removes inert nitrogen in the original air/fuel mixture. Another attractive characteristic is that the potential payback time rounds three years, depending on the price of natural gas
Conditioning and Forming	Single-Stage Forming	Mixes homogeneous forming temperatures with an aluminium tri-chloride lubricant to strengthen the surface of the glass. Emerging single-stage forming technologies could contribute to glass light weighting by preserving glass integrity while saving raw material and energy. Utilising this approach contributes to glass light weighting. However, glass conserves its integrity while saving raw material and energy. This technology can achieve up to 15% in cost savings while using less raw materials and energy.

7. General barriers and challenges to decarbonise the glass industry

Although we mentioned key barriers faced by each sector of the glass industry at the end of each section, here, we discuss challenges from an overall perspective or that were not mentioned before. In considering the barriers, we note that the most significant interventions on emissions are CCUS and fuel switching (**Table 7**).

Table 7: Technological potential for reduction of emissions in glass manufacturing. (Source: authors, compiled from[223])

Technology and process approach	**Technology**	**Technology Readiness Level**	**Potential of CO_2 emissions reductions**
CCUS	Carbon capture	N/A	Max 90%
Fuel switching to carbon-neutral energy	Fuel switch (carbon neutral gas)	8	75-85%
	Electric melting	9 (small furnaces) 5 (Large furnaces)	75-85%
Circular Economy	Increased use of recycled glass containers	9	Max 20%
	Increased use of recycled flat glass	9	Max 5%
	Batch palletisation	8	Max 5%
Process	Raw materials pre-heating	8	Max 15%
	Waste heat recovery	9	Max 15%

For CCUS, there are several general barriers to advance its implementation, including economic aspects, technical challenges, availability and sustainability of biomass, and public perception[317] [318]. Centring on the glass industry alone, since this is often a local industry, the most significant barriers for CCUS include the development and operation of storage sites, transportation costs, along lack of infrastructure. For fuel switching, gaps in knowledge and data and technical and economic barriers limit this technology's uptake. In addition, further R&D and investment are needed for the relevant technologies to take off (see **Figure 14**). Overall, and from a general perspective, many of our barriers relate to incentives, or lack thereof, for such investments.

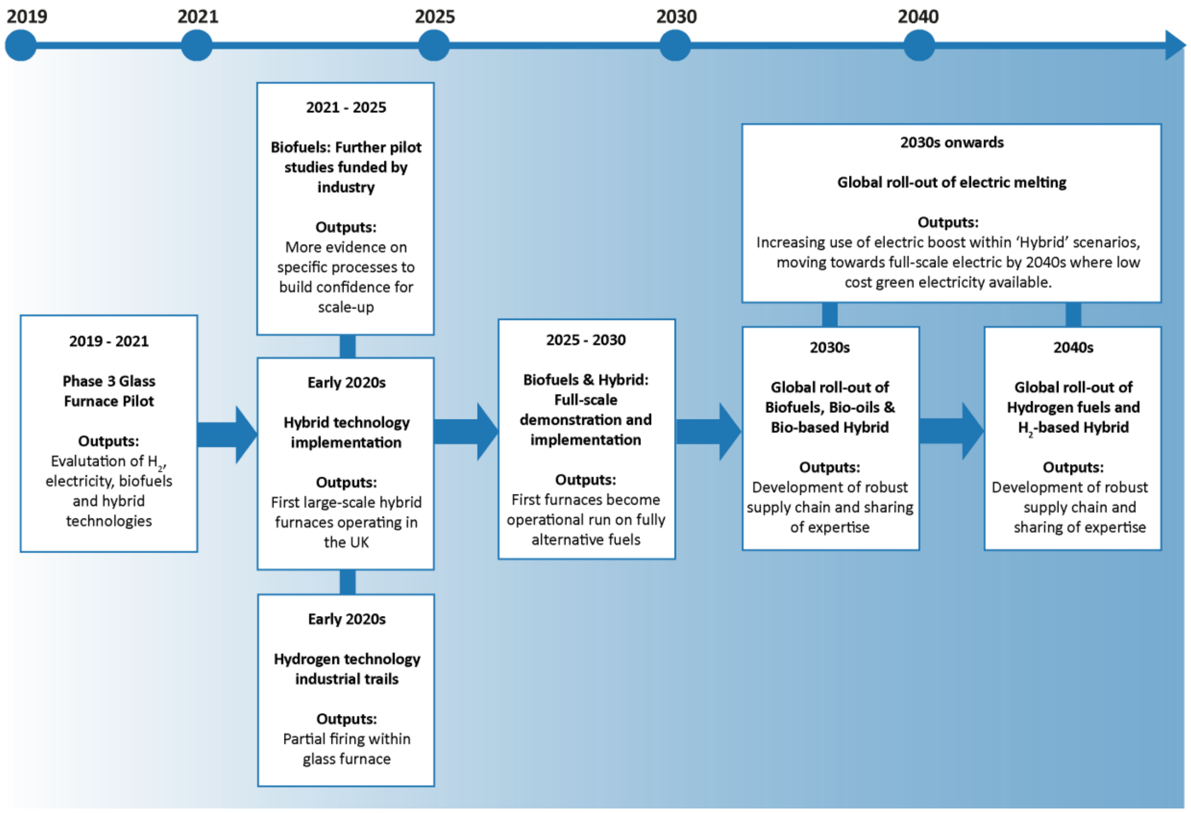

Figure 14: Estimated implementation timelines for the various fuel switching Options. (Source authors based on[219])

7.1 Financial costs and funding barriers

Starting with costs, we found a common barrier regarding unwillingness to invest in energy efficient measures with payback time above 3-5 years[38 30]. Certainly, one of the most critical barriers to decarbonise the glass industry is lack of funding for financing leaseback schemes and finding external financing opportunities (e.g., grants and RD&D funds)[11]. On this last point, reasons include: interest rates not allowing internal investment criteria to be met and lack of incentives to encourage companies to invest in decarbonisation measures[38]. We also note that there is a risk that companies may simply not be able to afford the upgrades, and therefore, government policies to stimulate investment may be the only way forward.

7.2 Carbon markets and prices

Meanwhile, others identified that the current market price of electricity is a crucial barrier for two reasons. First, high and fluctuating energy prices make it difficult to calculate the return on investment in new technologies. And second, high energy prices would make some technologies such as electric melting cost-prohibitive[20 39 319 320]. On this, BEIS notes that at least in the UK, there is uncertainty regarding the availability and economics of low-carbon fuels. In turn, it remains improbable that one fuel scenario only addresses the decarbonisation needs of the UK glass sector[219]. At the EU level, the glass industry's main challenges include downstream bargaining power, substitution by other products, competition, lack of security of supply, non-EU country trade barriers, and the counterfeiting of European designs[321]. Other issues are emerging from carbon markets; for instance, glass industries are exposed to 'carbon leakage.' An activity that occurs when energy-intensive industries belonging to the EU-ETS— in this case, glass—, transfer their production to non-EU countries with more lenient regulations, which could lead to an overall increase in GHG emissions[213]. For the EU glass industry, it is a top priority to avoid such practice and maintain its competitiveness since 80 % of its produced volume is traded within the EU.[224]. Since the glass industry shows high risk of carbon leakages, glass installations have received free allowances to mitigate the cost of EU ETS compliance. Research indicates that to avoid carbon leakage, producers should not be burdened with additional costs that hinder their ability to compete in the international arena,[322] carbon intensity, and trade intensity should be considered together through a combined indicator[323] and authorities must implement complementing policies such as technology support schemes and market introduction programs to mitigate the risks of carbon leakage[80]. On the social side, lack of skilled labour and lack of knowledge is an organization challenge,[237] although this is more evident for small-scale glass manufacturers[26].

7.3 Inconsistent Infrastructural support

Regarding technical barriers, one key challenge deals with infrastructure, since across countries, there are significant differences in furnace design, age and application. These elements influence in selecting the most appropriate pathway to decarbonise at given sites[225]. Technical barriers certainly represent the most significant challenge when, for instance, Christian Quenett, head of architectural glass at NSG Group, commented that *"The technical challenge [in decarbonising production] for us is huge... There is no solution on the horizon so far. Every company is doing some research work, but we are all too small to find the solution*[324]*."*

Regarding technologies and as mentioned before, full electric melting technologies are not yet available for large-scale plants, and hydrogen is not currently compatible with furnace infrastructure. Although biofuels seem like a promising alternative, there are barriers to costs, quality requirements, and distribution that make them unsuitable for the glass industry. There is yet another risk related to production disruption from retrofit technologies, namely the impact on plant-level employee performance KPIs for any process disruptions that might occur, which is an issue that particularly affects small scale companies[38].

As discussed in **Section 6.8**, recycling through the use of cullet reduces emissions from the manufacturing process; however, some barriers need to be overcome—for instance, low quality of existing cullet. According to our review, it is often the case that cullet does not own the properties to be re-melted in the glass-manufacturing process. The most common issues mentioned in this study that affected cullet use were related to colour separation and cleaning or separate contaminants (e.g., metals, lead, and aluminium). There were other concerns related to infrastructure; not all countries possess the facilities for glass recycling. Consequently, regulation regarding collection schemes is more advanced in the EU and other developed countries than in most developing countries.

8. Future research

A final finding from the systematic review is related to the literature gaps that need to be addressed in future research. We divide these into 4 areas, namely: insufficient information for future research, gaps in research beyond flat glass and glass containers, coupling to other sociotechnical systems and user behaviour and consumers' preferences.

8.1 Insufficient information on future innovations

We first note that there is a generalized lack of information regarding emerging and advanced energy-efficient technologies for the glass industry within the glass literature. Perhaps this issue is related to the variety of subsectors existing in the glass industry (glass applications often melt at different temperatures), the different sizes of glass manufacturing companies, and the different applications consumers demand in glass. We, nevertheless, noted that there are a significant number of studies that covered emissions abatement of the industrial sector from an overall perspective, but just a handful that focused solely on glass. This gap leads us to recommend that much greater focus should be placed on technological advances for the decarbonisation of the glass industry. Similar to what we have seen for sectors such as cement, iron and steel, and chemical, databases for relevant decarbonization technologies should be maintained for the glass industry and contain information on technology readiness levels and the global status of demonstration and deployment. The IEA is already doing this across industries and may lead to such an effort[325].

8.2 Gaps in research beyond flat glass and glass containers

Moreover, we noted that from those studies that did focus on energy and carbon savings (see **Section 6**), they narrowly focused on two glass subsectors, flat glass and glass containers. Along with this, the majority of the studies focused on the global north and China, with a handful of exceptions focusing on South Africa, South East Asia, and India. We did not find studies from the glass industry of countries such as Poland, the Czech Republic, and Mexico, which are among the top 15 glass exporters, generating 3%, 2.9%, and 2.3% of the global glass exports, respectively[326]. We could not find any studies related to glass industries in Latin America and sub-Saharan Africa. We acknowledge that flat and glass containers make up most glass products, and the countries that receive the most focus tend to have policies, data, and industry bodies most conducive to detailed study. Nonetheless, the lack of research in other subsectors of glass manufacturing and in developing countries offers an exciting avenue for future research.

8.3 Coupling to other sociotechnical systems

As noted in **Section 3**, the glass system does not exist in a vacuum, and like many other industries, is connected to other sociotechnical systems[327]. As shown in **Figure 15** below, the interconnections from the glass industry to other sociotechnical systems are prominent and range from the extraction of raw materials (e.g., sand and gravel) to critical materials in the construction sector electronics industries. Looking at the interconnection with the energy sociotechnical system, glass also plays an essential role not only from the energy consumption and electricity infrastructure perspectives but with regard to promoting efficiency within buildings and serving as an essential material in renewable technologies. Glass even touches on other sociotechnical systems such as transportation, food and beverages and chemicals. Finally the glass sector touches upon national and local regulation regarding recycling schemes, circularity and through glass picking, an opportunity to earn extra income or even become the "king of glass"[328].

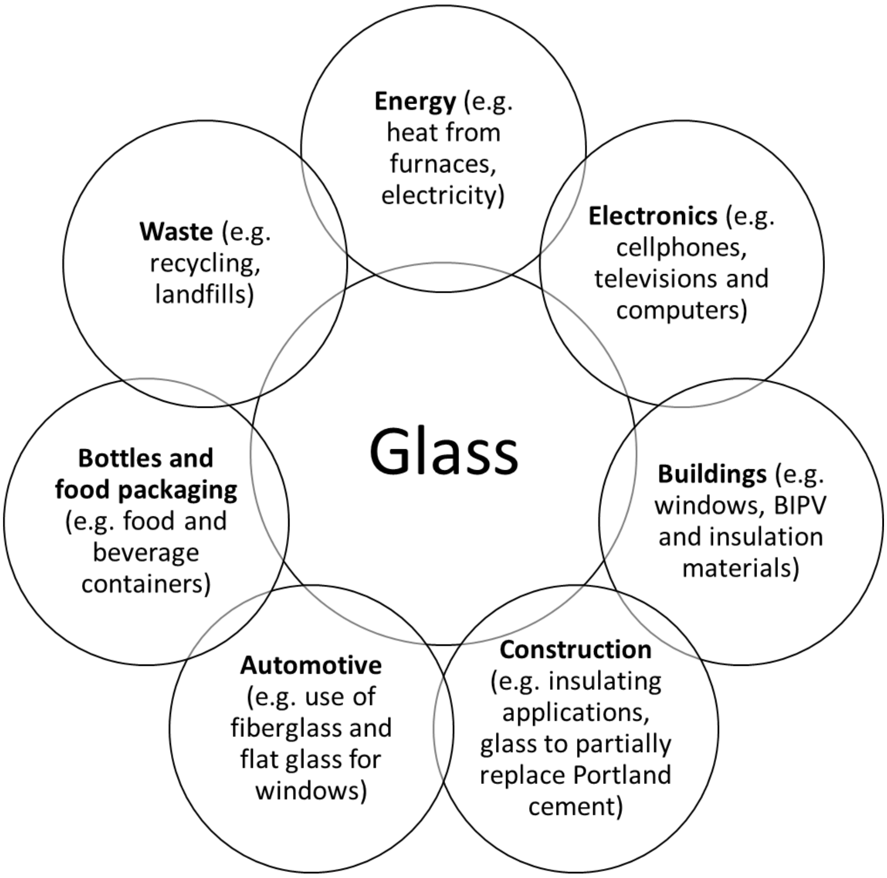

Figure 15: Compelling interconnections of glass to other sociotechnical systems. (Source: authors)

8.4 User behaviour and preferences and glass alternatives

We further call for future research regarding users' preferences and expectations for materials. For instance, acceptance of light weighted glass bottles (we could not find any studies on this), packaging colour and the acceptance of sterilized wine bottles are all key elements in mitigating emissions from the glass industry. Moreover, we echo the call from Guo and colleagues [143] to further investigate the role of glass in achieving low-carbon, yet high performance, concrete. Coupled to this, there is a general lack of understanding regarding the influence of glass' particle size and replacement percentage on the durability of concrete. Finally, more research should be conducted regarding substitute materials for glass so as to push industry for more environmentally friendly alternatives. In the automotive industry for example, vehicle production is the largest fiberglass consumer[106] and only a few studies explore this issue. We note, however, that major impact will only come through substitution for flat and container glass given their share of total glass production.

9.Conclusion

To explore the decarbonization of glass, we utilized a critical review approach with a systematic searching protocol and the guiding conceptual lens of sociotechnical systems. In this study, hundreds of documents were synthesized to help inform further academic research as well as industrial and governmental decision making for glass decarbonisation pathways. We asked: what alternatives exist to abate the climate effects of glass and thus make the full life cycle of glass more sustainable? What are the key determinants of the energy and carbon footprints from glass? What technical innovations have been identified to make glass manufacturing low or even zero carbon? What benefits will amass from more carbon-friendly processes in glass manufacturing, and what barriers will need to be tackled?

In answering these questions, our study notes that glass products are inherently intertwined with human development as they are used in the buildings we live-in, contain the food we eat and beverages we drink and provide the interfaces for us to see the information provided by our computers and smart phones. Glass is even a key component of the low-carbon future as it is used in the construction of renewable energy technologies and manufacturer of lighter-weight and lower-carbon transportation. However, regardless of such benefits, glass can be damaging to social and natural systems throughout its lifecycle. **Figure 16** illustrates (in white) glass environmental impacts from the extraction of raw materials (e.g. land degradation and biodiversity loss), the emissions caused from its production all the way to its final disposition.

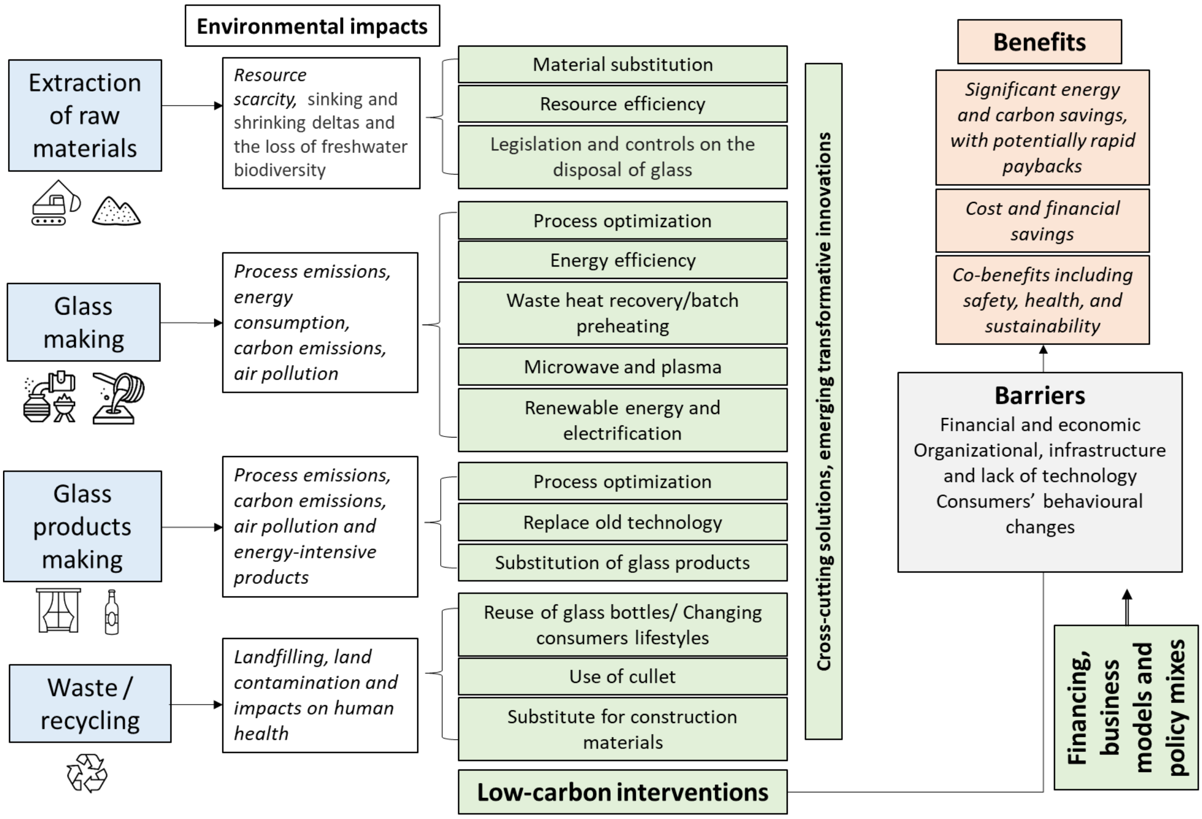

Figure 16: Interventions, benefits, barriers and policies for decarbonizing the glass sociotechnical system (Source: Authors).

Regardless of how complex, and environmentally damaging, this sociotechnical system is, **Figure 16** illustrates a number of possibilities shown in green that can mitigate emissions and even ameliorate impacts on the environment, biodiversity and human health. Possibilities for the extraction of raw material range from finding alternatives for glass substitution and resource efficiency to implementing more stringent legislation. Regarding the second and third steps (glass making and product making), **Section 6.10** presented no less than 31 technologies and processes that have the potential to promote energy efficiency, the use of renewable energy and mitigation of emissions from the industry. Although somehow discouraging, based on the evidence collected, we concluded that there is no agreed consensus on the most promising technologies for helping to achieve a net-zero, or even a lower-carbon future. Instead, the literature seems to indicate that the path for a decarbonized glass industry will most likely be slow with real progress starting only after 2030. For the last stage, we found that cullet supports the very important circular economy concept to mitigate emissions in the construction sector, particularly as a replacement for cement and concrete. Glass recycling also relates to government policy and consumers' behaviour as key means to mitigating the environmental impacts from the glass industry.

In **Figure 16** we present the barriers to decarbonize the glass industry. Supported by our review, the main obstacle is lack of economic incentive for decarbonization although lack of knowledge from small manufacturers to implement low-carbon processes and a general lack of demonstrated, large-scale low-carbon process options are key hindrances. At the consumers level, the main barriers are related to norms and behaviours regarding glass use and acceptance, or lack thereof, for new materials. The benefits, summarized in orange in **Figure 16**, indicate that for manufacturers economic and financial opportunities do exist with sustainability co-benefits (i.e., social, environmental and economic) perhaps having more salience impacts as the global focus on climate and sustainability increases.

In addition to breaking down how the glass industry impacts the environment, identifying low-carbon interventions and illustrating the relationship between glass and human development, our research offers promising avenues for future research. We call for further focus on the glass industry in developing countries as this would afford a great global impact from decarbonization and perhaps open up new lines of thinking related to business opportunities in developing countries. We further make a strong call to investigate consumer preferences regarding all aspects of glass bottles (e.g. weight, colour and re-use) so as to promote the adoption of more efficient materials.

In closing, we note that, as with industrial decarbonisation in general, strong policy frameworks will be needed to catalyse decarbonisation in the glass industry. Specifically, carbon pricing, R&D incentives such as tax breaks and subsidies to deploy new low and net-zero carbon and energy technologies in the glass industry are urgently needed to move the glass industry in the sustainable directions that we have highlighted.

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