COLECCIÓN **DIVULGACIÓN**

Welcome to the Glass Age

ALICIA DURÁN AND JOHN M. PARKER
EDITORS

CSIC

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Celebrating the United Nations International Year of Glass 2022

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Alicia Durán and John M. Parker (eds.)

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Madrid, 2022

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In this edition we have used ecological paper subjected to an ECF bleaching process, whose fiber comes from sustainably managed forests.

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Preface

It began as a debate on the use by historians of the terms Stone Age, Bronze Age and Iron Age. Had there ever been a time when glass was dominant? Could it be now? The concept of a 'Glass Age' took root in the USA, becoming widely promoted by organisations such as the American Ceramic Society and the International Commission on Glass. The success of the UN International Year of Light in 2015 suggested another line of thinking. Was an International Year of Glass feasible? After all glass and light are intertwined; and glass has a major role in areas such as communications, biomaterials, energy generation and conservation, as well as its products being inherently sustainable.

To justify a UN International Year requires a matching of aspirations to those of the UN, in particular the UN 2030 Sustainability Goals. This discussion began in 2016; thoughts matured into published articles. Progress could not be delayed by the onset of the COVID-19 epidemic in March 2020. Through the efforts of many excellent Scientists and Industrialists throughout the world, documentation was created showing the significance of glassy materials in promoting many of the UN goals. 2022 was identified as a year with many anniversaries of key historical events concerned with the manufacture and use of glass. Application was made to the United Nations. Following many twists, turns and delays in the process, the UN finally passed a resolution confirming that 2022 would be officially declared as a time to celebrate the International Year of Glass.

This text provides information on the personalities who developed the initial concept and the application process itself. It outlines the political steps and the value of contacts within the UN organisation. It is written with an intelligent young adult in mind, is richly illustrated and ties the wider glass industry firmly to UN aspirations. Some 13 chapters place glass at the centre and edges of human activity. Read it and join in the celebrations!

Alicia Durán and John M. Parker
Editors

JOHN M. PARKER, ALICIA DURÁN AND L. DAVID PYE

1. Creating a United Nations International Year of Glass

A seed is sown

In 2014 L. David Pye, Past President of The International Commission on Glass and The American Ceramic Society, learned that The United Nations General Assembly had declared 2015 an International Year of Light and Light-Based Technologies. As editor of *The International Journal of Applied Glass Science (IJAGS)* he realized that it was an opportune moment to showcase “Glass and Light” through a special edition. In 2016 a second special edition dealt with the emerging paradigm that we have entered *The Age of Glass*. David L. Morse and Jeffrey W. Evenson, senior administrators, Corning Inc., eloquently summarized this new thinking in their contribution “Welcome to the Glass Age” which was strongly reinforced by other contributions in this issue. Collectively and individually they argued that we are at a special moment in time where the arrival of *The Age of Glass* can be declared —with certainty and pride— by glass scientists, engineers, educators, artists, and glass manufacturers across the globe.

From all of this, it is clear that glass has played a major role in advancing civilization and mankind throughout recorded history be it in the arts, architecture, transportation, medicine, communication, and especially important, other branches of science. Had it not been for glass, the microscopic biological world might never have been revealed, nor would we have discovered the universe beyond the earth, moon, and stars. How can we not marvel that several centuries ago glass allowed light to enter darkened buildings while keeping away the cold,

Figure 1.1. Because glass is transparent it is often used for viewing other objects without being seen itself, for example when using microscopes, telescopes, optical fibers and binoculars.
Source: Pixabay.

rain, sleet and snow? How can we not marvel at the beauty and reverence of stained-glass artistry found in cathedrals across the world? Or the simple light bulb providing light for all we do when darkness falls? Or our increased ability to see by placing small pieces of curved glass before our eyes?

While many other revolutionary innovations can be cited where glass was the critical component in their development, the view here is that the greatest contribution of glass to life as we know it today is its role in advancing communication in ways unimaginable a century ago. Has not the world been transformed by the optical glass fiber networks that span the globe? Or by ultra-thin glass plates for television sets and protective covers for mobile phones? Then there is the remarkable story of a small company in Rochester, New York, that realized the potential of a light sensitive metallic glass for making possible high-speed reproduction of documents. This company was eventually renamed Xerox Corporation. Similar stories can be found in the emerging field of glass and healthcare. Notwithstanding this remarkable

Figure 1.2. A white filigrana vessel created using techniques similar to those now used for optical fibers.

Source: © Fondazione Musei Civici di Venezia - Museo del Vetro di Murano - Archivio Fotografico.

history, the view here is that the best is yet to come as glass science continues to evolve and be better understood [1].

Paradoxically, despite this history undergirding modern society, various texts written on nanotechnology rarely mention glass as *a quintessentially nanotech material*, while for glass scientists and engineers, the fabrication and application of glass begins and ends with their understanding physical and chemical phenomena at the nanoscale and below. Heralding the advent of *The Age of Glass* will help address this oversight and bring to the attention of the public at large the critical role glass has in our daily lives. Subsequent lectures by Manoj Choudhary, then ICG President, and David Pye given to international audiences explored the theme that glass science, engineering and art are entering new and profound chapters in their histories. Based on the above remarks, a sense of history, and appreciation of a seminal idea whose time has come it is a great honor to chronicle here and affirm the advent of *The Age of Glass*, and by extension a UN declared International Year of Glass.

Prompted by the very positive reactions to the above, David Pye discussed the concept of an International Year of Glass (IYOG) with Charles L. Craig, Senior Vice President, Science and Technology, Corning Inc. He was strongly supportive and encouraged its pursuit. Soon thereafter Profs. Choudhary and Pye introduced a motion in September 2018 at a meeting of the Council of the International Commission on Glass in Japan which read:

> *The International Commission on Glass, representing organizations and individuals throughout the world dedicated to the promotion of science, technology, artistry, and application of glass enthusiastically endorses the exploration of a future declaration of a Year of Glass by the United Nations.*

Following its positive reception, Prof. Pye presented the concept to the American Ceramic Society and the Corning Museum of Glass (CMoG). Both embraced the idea, the latter leading Steven T. Gibbs, a senior administrator at CMoG, to play a pivotal role in advancing IYOG 2022

Figure 1.3. Flag of the United Nations adopted in December, 1946.
Source: Pixabay.

to the international art community. Buoyed by this groundswell of enthusiasm, ICG's current President, Alicia Durán, took up the baton to become Chair of an International Steering Committee for the proposed IYOG. The die was cast.

Creating the right environment

Throughout the past 60 years the General Assembly of the United Nations has honored contributions to society in many fields by declaring '*International Years*'.

A UN badged International Year requires a United Nations Resolution. The Spanish ambassador at the Mission of UN in New York, Agustín Santos Maraver, agreed to lead the process through the United Nations and explained the steps and documents needed. The application finally submitted included a main document justifying the role of glass following the Goals of Agenda 2030, an eco-social document reporting state of the art in glass industry and an Executive summary. They showed how the glass community is supporting UN developmental goals (2030 agenda): responsible production and sustainability; innovation and infrastructure; affordable and clean energy; climate action; unpolluted water and oceans; sanitation, health and well-being; education and gender equality. From these documents, the final Resolution was written promoting glass, its past and future potential.

The chair of the group that led to the International Year of Light, Prof. John Dudley, University of Franche-Comté, willingly shared his experiences with an initial IYOG team consisting of Professors Duran, Pye and Parker and explained more of the procedures involved. In March 2020, talks with senior administrators of UNESCO were held after learning of its approval of a 2022 International Year of Basic

Figure 1.4. A stained glass window reminding us of a Green World outside needing our care.
Source: The Metropolitan Museum of Art Sansbury-Mills and Friends of the American Wing Funds, 2010, 2010.122a–d.

Sciences for Sustainable Development (IYBSSD) which included an International Year of Mineralogy. While 'competition' was the initial reaction, collaboration and mutual support with these groups were soon agreed to as the way forward. The IYBSSD, delayed by the COVID-19 pandemic, was finally approved at the General Assembly of UN on December 2nd 2021.

Being aware of their value and potential contributions the International Commission on Glass also approached several glass-based organizations as possible working partners. The International Committee of Museums, along with the Community of Glass Associations promoted by VITRUM and the Italian Government, accepted the challenge and joined ICG as sponsors of IYoG with many national Glass Societies to help.

A formal application for a *United Nations International Year of Glass for 2022* to celebrate the technological, scientific, artistic and economic role of glass as an enabling material crucial to many technologies and cultures was shifting from a possibility to a probability.

A seed germinates

Meanwhile throughout these initial negotiations written documentation was in preparation. A major 20 page document was created from an initial draft by Prof. John C. Mauro, the Pennsylvania State University, and enhanced/modified by many others drawing on information from numerous sources. Using an electronic format for easy circulation and with the help of David Moore, Managing Editor, The Society of Glass Technology, it was subsequently incorporated into an eight-page illustrated brochure. A document on the global economics of the glass

Figure 1.5. Sustainable development goals of Agenda 2030.
Source: United Nations.

industry was also generated from a variety of sources and national reports. As a supplement to these written texts, a thirty-minute video was created by Prof. Julian Jones, Imperial College, and Mathieu Hubert, Development Associate, Corning Inc. In addition to the main authors, many experts and colleagues collaborated in creating this splendid film and the documentation justifying our project; while too many to mention individually we would like to acknowledge their support; they were always ready to assist and overflowing with ideas.

The project grows roots

The next step was to generate international awareness and interest in the proposal for an International Year of Glass. Articles were written in Journals and Trade Magazines and a web site was developed. The documentation and videos created for the UN were also helpful as publicity. A LinkedIn site was started and Glass Societies throughout the world were contacted to circulate information.

To harness the enthusiasm generated, a contact form was made available on the International Year of Glass web site to gather the details of interested organizations and individuals. This created an invaluable database, and the associated statistical information became a significant part of the evidence submitted to the United Nations. Figure 1.6 is a chart showing the types of Institution offering support and Figure 1.7 indicates their geographical distribution.

Approaching the end of 2021 support has now been received from more than 2000 Universities and research centers, societies and associations, museums, artists, educators, manufacturers and companies in 89 countries spanning all five continents. Almost 1400 of these submissions offering enthusiastic support were received in time for inclusion within our final documentation submitted to the UN.

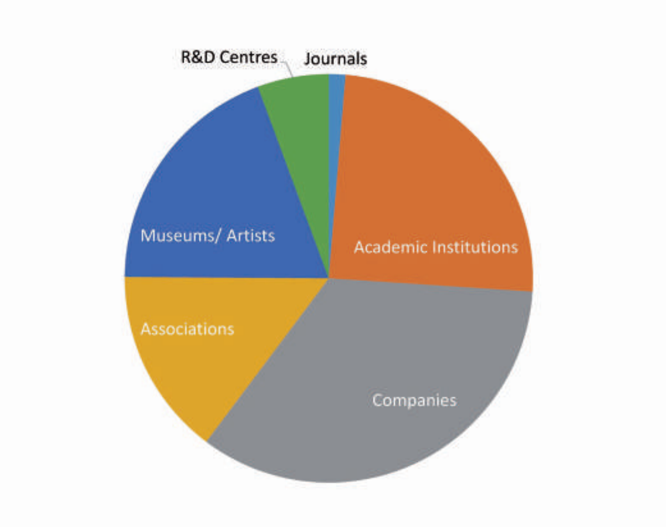


Figure 1.6. Showing the distribution of expressions of interest from various types of Institution.
Source: IYOG endorsers database.

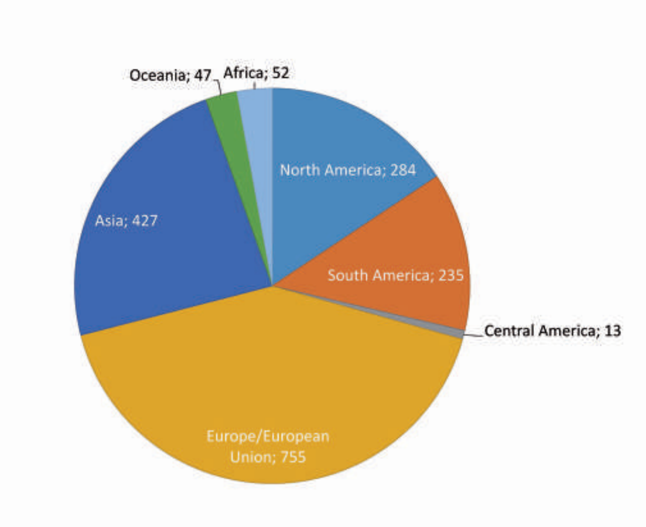


Figure 1.7. Showing the distribution of expressions of interest from different continents.
Source: IYOG endorsers database.

New partners are still welcome, particularly from the more under-represented areas such as Africa, and the Middle East. To join our circulation list email: manager@iyog2022.org and visit our web site (www.iyog2022.org).

Coming to fruition

The UN submission was far from smooth because of frequent false starts caused by the effects of the COVID-19 pandemic and also by the sensitive nature of the politics behind such submissions. Dates anticipated for a formal submission came and went with no action because important international meetings were delayed or not everyone was yet agreed on the details of the submission. Eventually a draft Resolution outlining our ambitions was negotiated and accepted by the Missions of several UN countries during April 2021. It successfully passed a silent process of approval on 11th May —no one had objected. The formal resolution was agreed at the United Nations General Assembly on May 18th, 2021 during a meeting that took place on-line; several committee members sat glued to their seats during the proceedings and their response to the vote echoed around the world.

Heartfelt thanks go especially to the Spanish Mission at the UN, particularly the Spanish ambassador Agustín Santos Maraver and Ana Alonso Giganto, who led this process through the difficult twists and turns of diplomacy in stressful times. We are also grateful to the 19 countries that lent their support as Co-Sponsors by formally endorsing the UN resolution.

Supporting growth: running an IYOG

From the start was a realization that such celebrations could not be organized solely by one committee;

Figure 1.8. United Nations Headquarters, New York.
Source: Pixabay.

local communities had to be harnessed for local activities.

The task of diffusion and coordination of thousands of activities across the planet has started: congresses and seminars, industrial fairs and glass schools will co-exist with artistic exhibitions, books, social media, scientific, technical and general interest magazines. Event planning is relying on grass roots input and a network of volunteers; delegation is indispensable.

Regional Organizations have been created based on location, language and the geographical distribution of endorsers across the planet. These total 18 groups and they are listed in Table 1. Each group will focus on coordination, advertising, sharing best practice and providing a supportive environment. Additionally, an Executive Committee, based on representatives from the Regional Organizations will promote the best ideas and multiply their impact. Financial arrangements for local activities are being dealt with at a local level but a Sponsorship Program has been created to support internationally activities, particularly the Opening Ceremony a UN ‘requirement’. Finally, an overarching small executive committee is able to identify issues, react quickly and offer guidance as the need arises.

The internet, underpinned by glass fiber cables, and viewed through glass screens is supporting communication. One positive outcome of the Pandemic is the rapid growth in tools such as Zoom and Teams to allow widely separated groups to meet and communicate efficiently. We are also designing a framework to record, develop and share ideas across the glass world based on our web site (www.iyog2022.org) and a LinkedIn group *International Year of Glass 2022* exists.

Looking to the future, a successful sustainable development agenda will require partnerships between governments, the private sector and civil society built on principles and values, a shared vision and goals with people and the planet at the center; partnerships are needed at global, regional, national and local levels. An IYoG will initially underline the varied roles of glass but should also stimulate, mobilize and redirect such partnerships to unlock their resources and deliver sustainable development over the long term.

Major events planned

The original application was formulated around several significant historical anniversaries. These included the 670th anniversary of the earliest depiction of eyeglasses in a painted work of art (frescoes dated 1352 by Tommaso da Modena in Treviso, Italy); the 200th anniversary of the invention of the

Group 1	Brazil
Group 2	Germany, Liechtenstein
Group 3	China
Group 4	Turkey, Greece, Cyprus, Malta, Jordan, Saudi Arabia, Lebanon, United Arab Emirates, Bahrein, Israel, Bulgaria
Group 5	Argentina, Bolivia, Chile, Peru, Uruguay
Group 6	Mexico, Costa Rica, Dominican Republic, Ecuador, Guatemala, Colombia, Venezuela, El Salvador, Panama
Group 7	USA, Canada
Group 8	Spain, Portugal, Andorra
Group 9	France, Belgium
Group 10	Japan, Korea
Group 11	Denmark, Finland, Norway, Sweden, Netherlands, Luxembourg, Latvia, Estonia, Lithuania
Group 12	UK, Ireland
Group 13	Russia, Poland, Armenia, Kazakhstan, Belarus, Uzbekistan, Moldavia, Ukraine
Group 14	Hungary, Slovenia, Serbia, Rumania, Slovak Republic, Czech Republic, Switzerland, Austria, Croatia
Group 15	Algeria, Angola, Egypt, Eritrea, Morocco, Nigeria, South Africa, Swaziland, Tanzania, Ghana
Group 16	Australia, Malaysia, New Zealand, Singapore, Vietnam, Indonesia, Philippines, Thailand
Group 17	India, Iran, Pakistan
Group 18	Italy

Table 1. List of regional groups and the countries included in each.

Fresnel Lens used in seashore lighthouses and attributed with preventing countless disasters; the 100th anniversary of the discovery of ancient Egyptian Glass in King Tutankhamun's Tomb in 1922; the Centennial Anniversary of the German Society of Technology (DGG); the 70th anniversary of the Pilkington patent in 1952 that heralded the *float glass process* and forever changed flat glass manufacture; the 60th anniversary of the Studio Glass Movement; and the 45th anniversary of the Nobel Prize to Anderson and Mott for work on amorphous materials.

Events currently agreed are: an Opening Conference in Geneva from 9-11th of February; '*From Pharaohs to High Tech Glass*' in Egypt, April-May 2022 (celebrating 100th anniversary of the discovery of ancient Egyptian Glass in King Tutankhamun's Tomb); a *US Glass Day* in Washington DC, April 2022; an ICG International Congress in July in Berlin to celebrate the 100th anniversary of DGG; several *International Glass Art festivals and Museum events* in Europe and USA; finally a *Closing Congress in Japan*, on 8-9th December 2022. Additionally, there will be an Iberoamerican International Congress on *Women in glass: Artists and Scientists*, Madrid. Also planned are the XI Fórum técnico para la conservación y tecnología de la vidriera histórica, Barcelona 2022 and the 16th International Conference on the Physics of Non-Crystalline Solids in Canterbury, UK.

Several Trades Fairs and exhibitions are planned, most showcasing the history of glasses and glass making: *VITRUM*, Milano, 5-8th October 2021, the *China International Glass Industrial Technical Exhibition* and Glass Week with *Hi-tech Industrial Congress* and other glass knowledge literacy events, Shanghai, 11-15th April 2022; *Glasspex/Glasspro* at Mumbai (March 3-5th, 2022) including Glass Week; *GLASSMAN*, in Monterrey (11-12th May) with satellite events; *MIR STEKLA*, at Moscow (6-9th June); and *Glasstech*, including Glass Week, Düsseldorf 20-23rd September 2022.

Figure 1.9. Nations from all 5 continents are working together to support activities across the globe.
Source: Pixabay.

Figure 1.10.
An elaborately
decorated glass beaker.
Source: *Turner Museum of Glass* (Simon Bruntnell).

Dedicated issues of international journals will be published and exhibitions are planned in museums, public and private glass collections. Educational materials are being prepared for universal dissemination.

For example, the Spanish Research Council, CSIC, is committed to publishing this celebratory book and organizing exhibitions on: a) IYOG objectives and b) creating a Circular Economy based on recycling and glass containers. There will be a re-edition of *Glass Houses* and a *Glass and architecture exhibition* focused on sustainability. The preparation of a *Circular Economy exhibition* was designed with the participation of ANFEVI and ECOVIDRIO and the support of FEVE. English and Spanish versions of exhibition materials will be offered to all supporting countries with translation into local languages a possibility.

Another important task has been fundraising, particularly to finance the opening event in Geneva. At the time of writing, individuals and organizations can contribute directly through the IYOG web site but there are also numerous sponsorship opportunities for the formal Open Ceremony in Geneva, designed to kick-start the whole journey.

Summary

IYOG2022 is a dream come true, one we scarcely dared to anticipate. We are moved by the possibilities, prepared for challenges ahead and limited only by our imaginations.

The application to the UN was based on the UN 2030 humanitarian and sustainability aspirations. This book goes on to examine each of the goals considered in the original application and looks in greater depth at what glassy products can contribute.

References

[1] Liu, C. & Heo, J. (2015): “Band Gap and Diameter Modulation of Quantum Dots in Glasses”, *International Journal of Applied Glass Science*, 6 (4).

JOHN C. MAURO AND JOHN M. PARKER

2. Glass History and the Arrival of the Glass Age

THIS chapter explores the history of glassmaking and its role in advancing civilization throughout recorded history, highlighting the enormous contribution glass has made to human society over millennia and how it still plays a vital role, perhaps more than ever. It builds on the arguments in Chapter 1 that we now live in the 'Glass Age' and many themes introduced here are expanded in later chapters. Typically, glass is a material we look through, so its importance is often unseen and unnoticed; this book aims to redress that imbalance.

Glass compositions

Using the term 'glass' is a little like calling a steel girder, a copper wire, an aluminum can or a brass doorknob simply 'metal'. Glassy products have many compositions and fabrication routes according to their end use. Mostly, glasses are made by melting appropriate raw materials, then shaping and cooling back to room temperature without crystallization. The composition and chemistry define what wavelengths of light are transmitted; the melting process is designed to create a bubble- and crystal-free homogeneous product with no internal boundaries where a refractive index step would scatter light and destroy transparency. Consider for a moment how effectively finely ground icing sugar hides the imperfections of the cake underneath because of those boundaries between the many small but individually transparent sugar grains. Most common glasses have silica (sand) as a significant component and this chapter begins with silica-based

Figure 2.1. Egyptian container.
Source: *Turner Museum of Glass* (Simon Bruntnell).

products. They readily form glasses because their melts are viscous, and their interlinked atomic components cannot easily re-arrange into regular crystal structures. Their high viscosity also makes shaping into containers, sheets, fibers and tubes possible (see Chapter 13).

Glass making, its origins

Society has used glassy materials for millennia. Initially these were naturally occurring, particularly obsidian, a rapidly cooled volcanic lava which had failed to crystallize. It was sculpted into arrowheads which could be used to catch food and axe heads which could shape wood. Smaller pieces became jewelry and larger pieces were even polished to make mirrors.

As human society developed and learned how to control fire, the skills of the metallurgist were developed giving the Bronze Age. Somewhere someone discovered that the same heat sources could melt sand *if* a flux was present. The early fluxes used particularly by the more advanced societies in the Middle East were white salts rich in sodium and potassium, although they didn't know that! Such materials are found on the shores of dried-up lakes (Wadis) in the Nile basin for example and in the ashes from burning plants. These were actively traded because of their value in medicine, as detergents and in dyeing. The metallurgists and glass makers would also no doubt have shared their skills in furnace technology.

Over the centuries, the raw materials used evolved. Purification/beneficiation processes improved, compositions changed to introduce color, increase chemical durability, and create products with optimized characteristics over a wider range of properties. Archaeologists now use compositional information (elements and their isotopes) to uncover ancient trade routes, to identify the sites of glass works, the source of their raw materials, and the distribution of the finished products.

Figure 2.2. Glass blower at work, shaping a blown sphere before 'cracking off'.
Source: Pixabay.

Shaping glass hollowware

History is full of milestones, turning points where advances in glass stimulated change: Over 3000 years ago, exquisite Egyptian glass bottles were made for expensive perfumes by trailing molten glass around a solid core; just before BC became AD, glass-blowing was developed, probably in regions that now lie in Syria, and quickly spread throughout the Roman world. Before long, this approach was creating intricate and collectable objects. Surface decoration could be added perhaps using a rotating wheel and abrasive on a foot-operated lathe. 4th century Romans at the pinnacle of their glass-making

skills probably used this approach to make the posts which supported the complex coloured glass cages around luxurious '*diatreta*' vases. Appropriately, ancient writers equated the glassblower's breath with the wisdom of the philosopher Seneca.

Dating the different steps in the development of production processes is often by association. For example, glass vessels were used as burial urns and contained items needed in the after-life such as dated coins or personal memorabilia. It is now 100 years since the opening of King Tutankhamun's Tomb in Egypt. He reigned for a short period around 1330 BC, and glass items were discovered in his tomb. A millennium ago, elaborate goblets celebrated dynasties, while decorated mosque lamps spoke of a patron's generosity.

From the time of discovery until the 19th century, glass blown containers went through many changes. Color, for example, was introduced for artistic effect, to identify ownership and warn of dangerous content (blue medicine bottles). Another key change has been the method of sealing. Hand-blown glass has to be attached to a 'blowing iron' until almost the end of the shaping process; the neck is formed as a final step and requires re-heating. Creating an accurately and repeatably shaped 'finish' is difficult and impinges on the quality of the final seal; a poor seal means diminished 'shelf life'. Of course, historically the introduction of corks went part way to solving this. But it was not until machine forming came along towards the end of the 19th century and beginning of the 20th century that screw top seals could be used. Such considerations were vital in the development of glass containers for perishable foods. Indeed, the screw top 'Kilner' jar underpinned the preservation over winter of fruit in jams and in syrups at a time when sugar taxes were being abolished in the UK, making the process economic.

The modern glass container industry has machines creating hundreds of bottles a minute from a single furnace, with an accurately profiled shape, excellent resistance to attack and 100% recyclable. It remains a major force in the marketplace with global sales near US$ 53 billion, split between beverages, cosmetics, food, pharmaceuticals and others. Beverage packaging is dominant and wine bottles are two thirds of this total. Market expansion is driven by exports and continued demand for packaging made of glass.

A vital attribute of glass is the capacity for designing unique profiles identifying a brand. Other factors are transparency and chemical inertness, ensuring long-term preservation of taste and visual impact. Weight

Figure 2.3. A glass container with a seller's seal for identification (17th/18th century).
Source: *Turner Museum of Glass.*

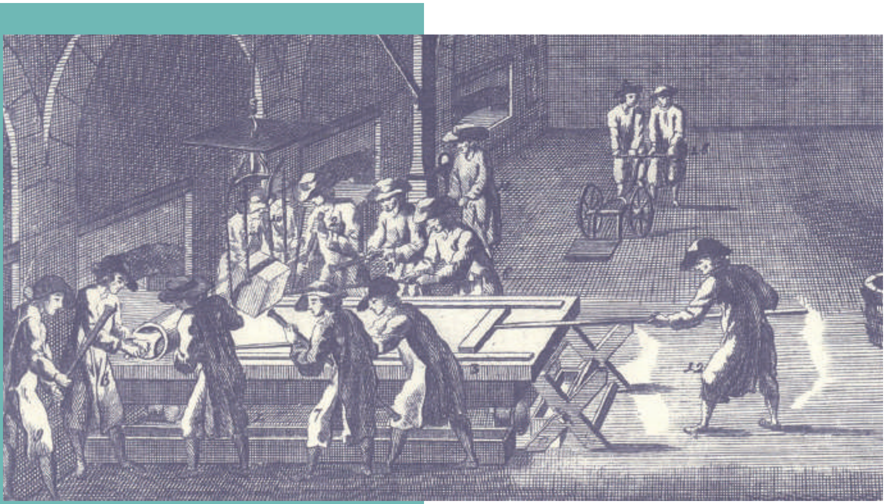


Figure 2.4. Early production of large glass sheets.
Source: Diderot and D'Alambert *Encyclopedia*.

is a disadvantage, but the industry is working hard on light-weighting. It is also investing in new products, increased energy efficiency and improvements in the environmental performance of glass products throughout their lifecycle (Chapter 7). Future success will require companies to adopt 'smart technologies' that improve consumer experience and maintain product integrity across the supply chain.

Such trends are universal. For example, Chinese colleagues report that glass is becoming the packaging material of choice for their government. The Chinese glass container manufacturing industry has experienced continuous growth in recent years. Aggregate operating revenue in glass-packaging container manufacturing industry was 61 billion RMB in 2019. As a green product, the glass container surely offers extensive development possibilities.

Of particular significance are the chemically resistant glass containers for pharmaceutical use (vials, ampoules, syringes, cartridges) obtained by converting neutral borosilicate glass tubes (300,000 tons in 2019 growing rapidly at 10-20% p.a.). This has been driven recently by the world's quest to deliver a vaccine to fight the COVID-19 pandemic.

Glass is still a unique commodity in today's materials market. Used every day by billions of people, glass containers present countless advantages for both consumers and the environment. Being 100% recyclable, glass can be melted and reformed an infinite number of times (Chapter 8).

Glass for windows

Early glass makers were unable to produce a flat glass product suitable for glazing and the first evidence for its availability is from early Roman times. Although glazing allows light to enter while keeping bad weather at bay, it is a weak point under attack and so needs a stable society. Until the end of the Middle-ages glazing was a luxury and panes were small. By this period two early methods used by Roman Glass Makers were becoming popular —crown

and cylinder glass. Both began by blowing, a process that, without intervention, tends to create spheres. In crown glass a hole is created in the 'bubble' which is then spun rapidly so that it opens out into a disc with characteristic circular markings. In cylinder glass a large sphere is allowed to extend vertically under the influence of gravity to create the required shape. Once made, the cylinder can be opened into a sheet by making an extended crack along one side and opening the cylinder up inside a hot furnace using long wooden rakes. Such methods were incapable of creating distortion free

Figure 2.5. Stained glass window from a church.
Source: Pixabay.

unblemished flat glass surfaces of large size. Hence the use of lozenge shaped pieces no bigger than the palm of a hand in earlier architecture and small rectangles with elegant fine glazing bars in Georgian times.

At the turn of the 19th/20th centuries, just as automatic bottle production was beginning, so were machine methods for flat glass manufacture introduced. One example was the Fourcault method where a long refractory boat with a slot along the bottom was pressed into the hot glass surface and as the melt welled up through the slot it was taken and drawn vertically by edge gripping rollers. This gave much larger sheets.

Some applications, though, required better quality surfaces than any of these methods could achieve, for example, carriage windows and mirrors. Such products required the grinding and polishing of cast sheets. This was labor intensive, so the products were expensive and only available to the rich or very rich, particularly in earlier centuries. Now though the mass production of mirrors, each reflecting a clearer personal image, has stimulated the international cosmetics trade.

A major breakthrough came with the creation of the Float Glass process patented in 1952, 70 years ago. This creates one free surface and an undersurface floating in molten tin. Both are effectively distortion free. Float methods were able to give glass thicknesses from 25 mm down to one millimeter. Of course, development never ceases; the screens of mobile phones are just 0.5 mm thick and prompted the invention of yet another sheet production technology. A millennium ago, glass windows flooded our sacred buildings with light, and now we view the world and ourselves through glass —our phone screens, our mirrors and our architectural skyline.

In transport, glazing allows unimpaired vision and contributes to safety and security, as well as style. Airplane cockpit windshields are chemically strengthened. Innovative designs offer thermal comfort; improve fuel efficiency by light-weighting; and integrate display features.

Two-thirds of flat glass production is used in architecture, while most of the rest is for the transport industry. These applications often involve secondary processing, for example cutting, grinding and polishing. Surface treatments add considerable value by conferring characteristics such as self-cleaning, chemical resistance, light and heat transmission control for thermally efficient glazing, electrical behavior, and increased mechanical strength (Chapters 4, 6).

Plant construction is capital intensive, needs appropriate expertise and has traditionally been limited to a few major players, but markets now influence the location of new facilities. After the 2008 recession, fewer than 200 factories and 400 production lines remained, but then entry barriers fell and expansion began in emerging markets such as the BRIC countries (Brazil, Russia, India and China). In the last 15 years, Russia has quadrupled its production plants to 8 while India has almost doubled to 7. Other developing markets are Asia, Africa, the Middle East and South America. Algeria, Kyrgyzstan, Malaysia, Syria, Ukraine and Vietnam have all recently built furnaces.

Since 2015, China's flat glass production capacity has grown particularly rapidly, mirroring its economic development; in 2019, capacity exceeded 60% of the global total, causing a significant surplus. China's environmental protection and capacity replacement policies were subsequently tightened, restricting new production capacity. This required rapid industrial structural adjustment and diversification to higher-quality products.

Now, China's building and transportation industries are growing rapidly again and fundamentally changing to energy-saving, safe, and lightweight products. Green building is adding 1.6-2 billion m^2 annually to 60 billion m^2 existing floor area, 90% of which is in high-energy-consumption buildings that urgently need transformation. So the processing of energy-saving insulating glass,

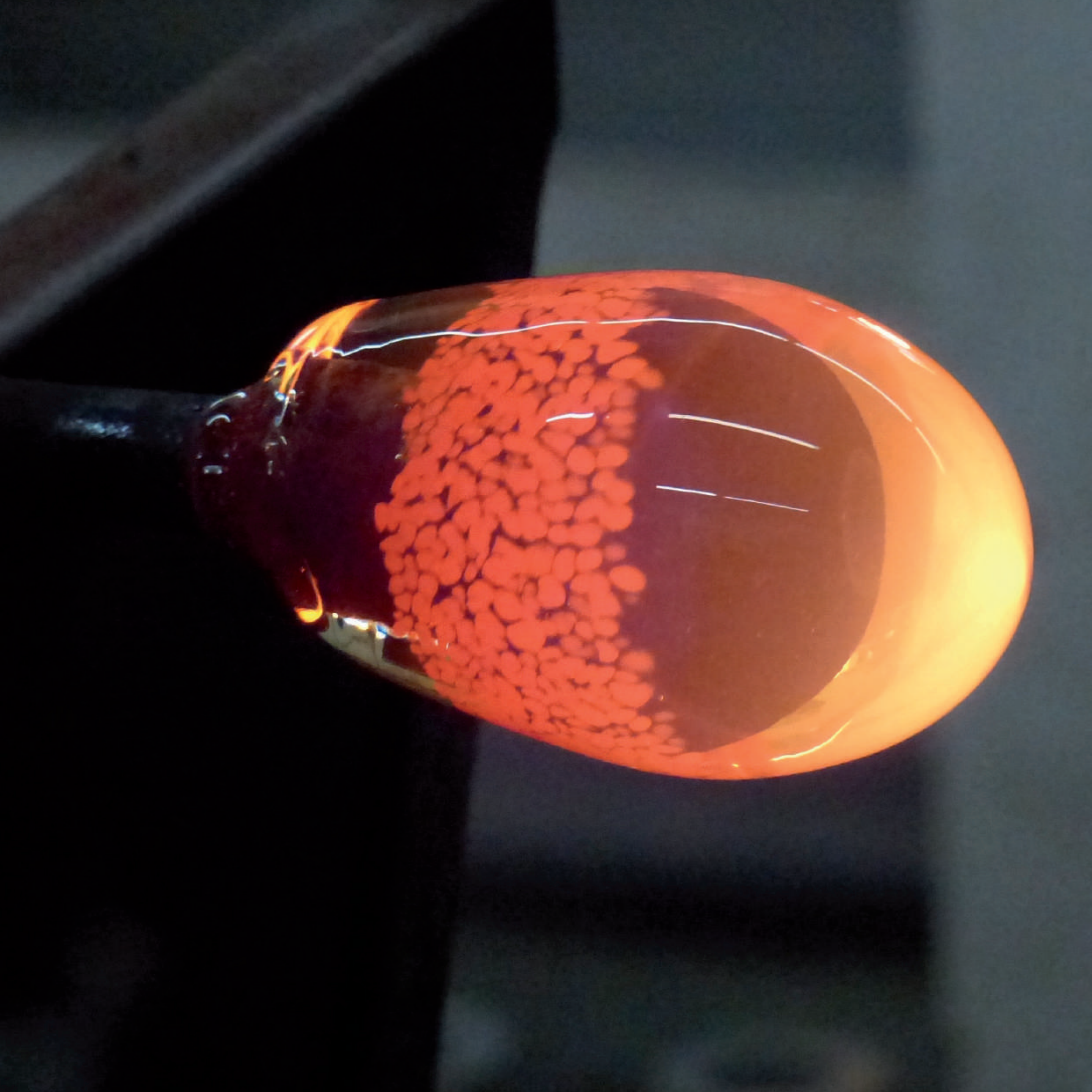
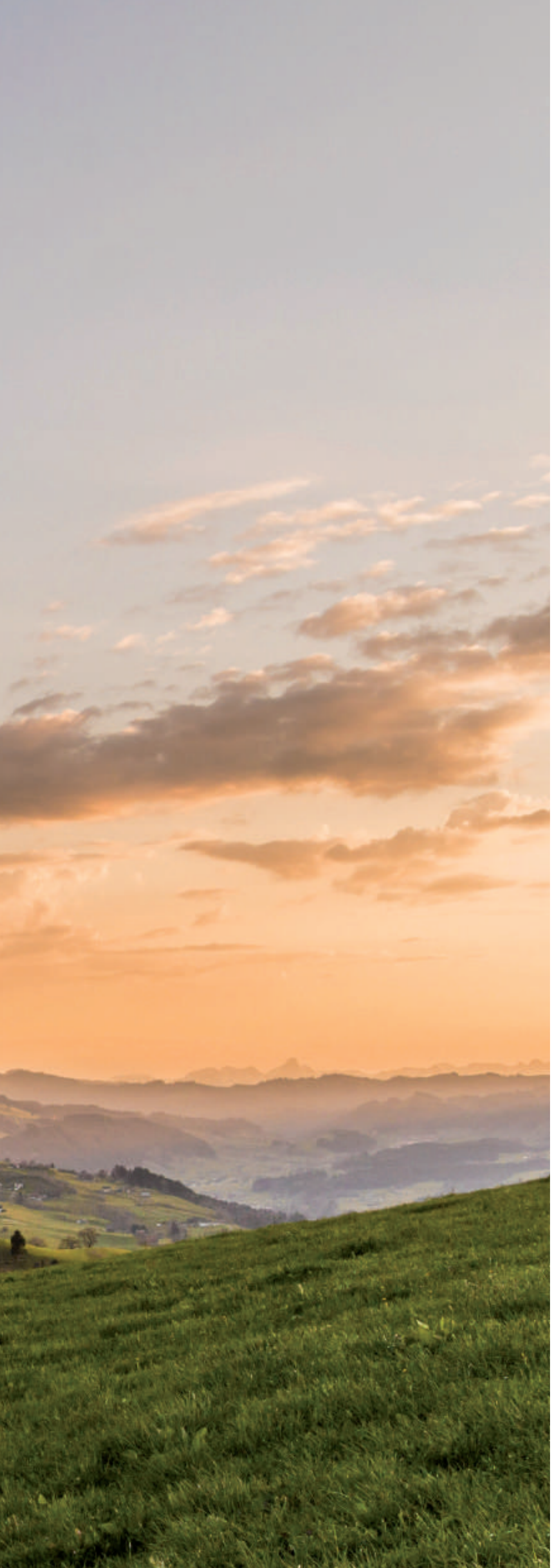


Figure 2.6. The blades of wind turbines are reinforced plastics using glass fibers with a high Young's modulus.

Source: Pexels.



tempered vacuum glass, electrochromic glass, flameproof glass and other products will expand rapidly.

China is now the largest car producer and consumer worldwide. In 2019, it manufactured almost 26 million vehicles, more than 40% of the global total. The operating mileage of high-speed railways is almost 35,000 km, 2/3 of the world's total. Such developments offer new opportunities for glass. China is also the largest producer of Ultra Clear Photovoltaic flat glass, with 3 million tons in 2016, over 70% of global market share.

Glass fibers

Glass fibers exist in nature and are called Pele's hair. They arise when strong winds catch a hot lava flow and create thin glass strands. Glass fibers have been made commercially by pulling thin strands singly from heated glass rods and indeed have been woven into cloth. But glass fiber made as multifiber bundles (rovings) is valuable in construction, particularly for reinforced plastics; the global market currently is approaching US$ 10 billion p.a. A key application is pipework for transmission of water and other strategic liquids; storage tanks and baths for water are also important. Such applications are particularly significant in the Middle East where atmospheric conditions are extreme, and soils often saline; both cause rapid corrosion of alternative materials. China again is a dominant player with a 30% market share; the Middle East has key manufacturers and the USA market for these products is expanding too.

In 2019 China's total glass fiber output was 5.27 million tons, up 13% year on year, with a product yield of 4.5 million tons. With increased globalization of glass fiber products, up to 20% of Chinese glass fiber and relevant products are being exported.

In the future glass fiber products are expected to displace steel, aluminum, wood, PVC, and other traditional materials. Building, transportation and electronics industries offer enormous potential. According to the Trend Forecast and Opportunity Analysis of Global Glass Fiber Composite Market Report, the overall global glass fiber composite consumption will grow at 8.5% p.a., with the market size in 2022 expected to be up to 108 billion RMB. In the next 5 years five key fields —auto firmware, building decoration, safety protection, aerospace and liquid filtration— will take up 80% of glass fiber composites.

The glass fiber market has many other sectors based on novel glasses (chemical resistance, elastic moduli) and different fiber formats. A vital market is wind turbine blades, a low carbon source of almost 20% of the world's electrical energy; another is insulation

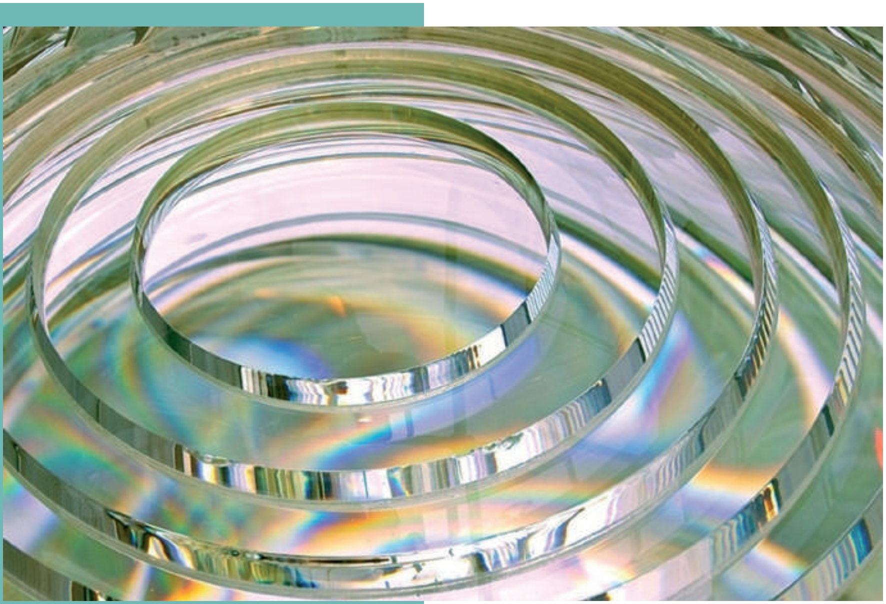


Figure 2.7. 3D printed optical glass artefact.
Source: iStock catalogue.

(Chapter 4). Optical fibers are the subject of Chapter 5.

Glasses and light

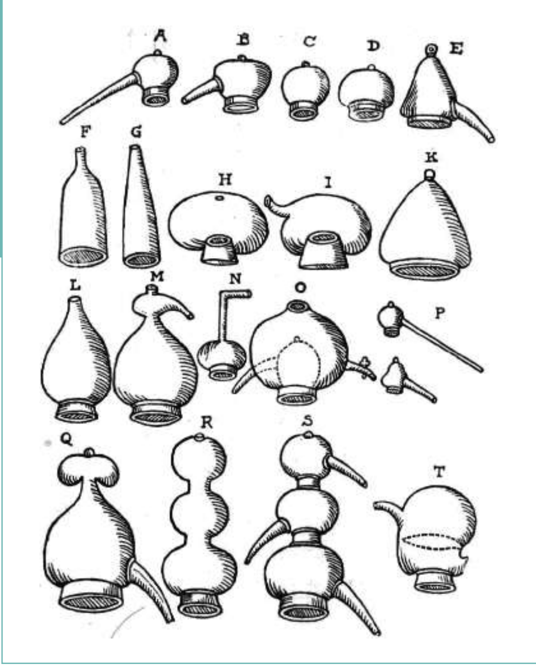
Long ago tailors realized that a glass globe filled with water could focus the light of a candle to aid stitching after the sun had set. More recently glass light bulbs provided an impervious envelope for incandescent lamps, preventing filament oxidation, and a vacuum for electrons to flow in fluorescent lamps; these developments have encouraged reading as well as extending the working day and earning potential of poorer families. For 200 years, glass Fresnel Lenses in coastal lighthouses have beamed the light from huge lamps to distant vessels, warning of danger using a lightweight structure.

Monks realized that eyeglasses eased the strain of creating illuminated manuscripts and 2022 is the 670th anniversary of the first depiction of eyeglasses in a painting. Many famous scientists such as Faraday studied glass lenses and their focusing power and Galileo's telescope opened our eyes to the wonders of the cosmos; the latest developments in telescopes with glass lenses in space are allowing scientists to see back to the very beginnings of the universe. Microscopes have let us study cells and microbes and so understand diseases. Behind such developments since the 19th century have been major research studies on the relationship between glass properties and composition and these have led to the capacity to design compositions to fit a particular property profile. Important players in glass optical property development have been the Germans and it is appropriate that 2022 celebrates the centenary of the German Glass Society.

Glasses and measurement

Glass being transparent, hard and inert has allowed the creation of many different instruments. Important

Figure 2.8. A variety of glass objects made for the Alchemists of an earlier age.
Source: Andreas Libavius.



examples are the thermometer and barometer, which in turn initiated an understanding of weather forecasting and even chemical thermodynamics.

Glasses, water and energy

In the last century, billions of people have experienced an unprecedented rise in living standards, but many still live with little access to clean water. Sufficient fresh water exists but damaging economics or poor infrastructure cause millions to die annually from diseases linked to inadequate supplies, sanitation, and hygiene. Similar issues impact adversely on food security, life choices and educational opportunities.

Industrial discharges, excess agrochemicals and domestic waste landfill contaminate surface and groundwater. Glass can mimic current water treatment processes. Porous foam glass or phase separated glass filters can aid sanitization (and purify air, another global issue). Sunlight on coated glass immersed in solutions of organic pollutants can oxidize many into non-toxic products and likewise restore drinking water. Most cost-effective is a combination of porous glass filters with titania-coated glass.

Energy with water epitomize the opportunities and challenges the world faces. Universal access to energy is also crucial to build more sustainable and inclusive communities and in turn entails more efficient generation, renewable energy sources and ways to store it. This theme is taken up in Chapter 4.

Glasses and medicine

Scientific endeavor has also relied heavily on glass. The alchemists of the Middle Ages made complex glass equipment to pursue their dreams of chemical transformation and incidentally created a tool-box for apothecaries (Figure 2.8). In the last few decades glasses have themselves become the biocompatible and bioactive products that have been universally life changing for patients; much more can be found in Chapter 3.

Glasses for communications and electronics

The use of glass envelopes for lighting revolutionized our capacity for making lamps and fluorescent tubes during the late 19th century. Similar technology led to a revolution in electronics. In the UK many disabled soldiers were trained in lamp working at Sheffield University and the electronics industry between WW1 and WW2 grew largely based on

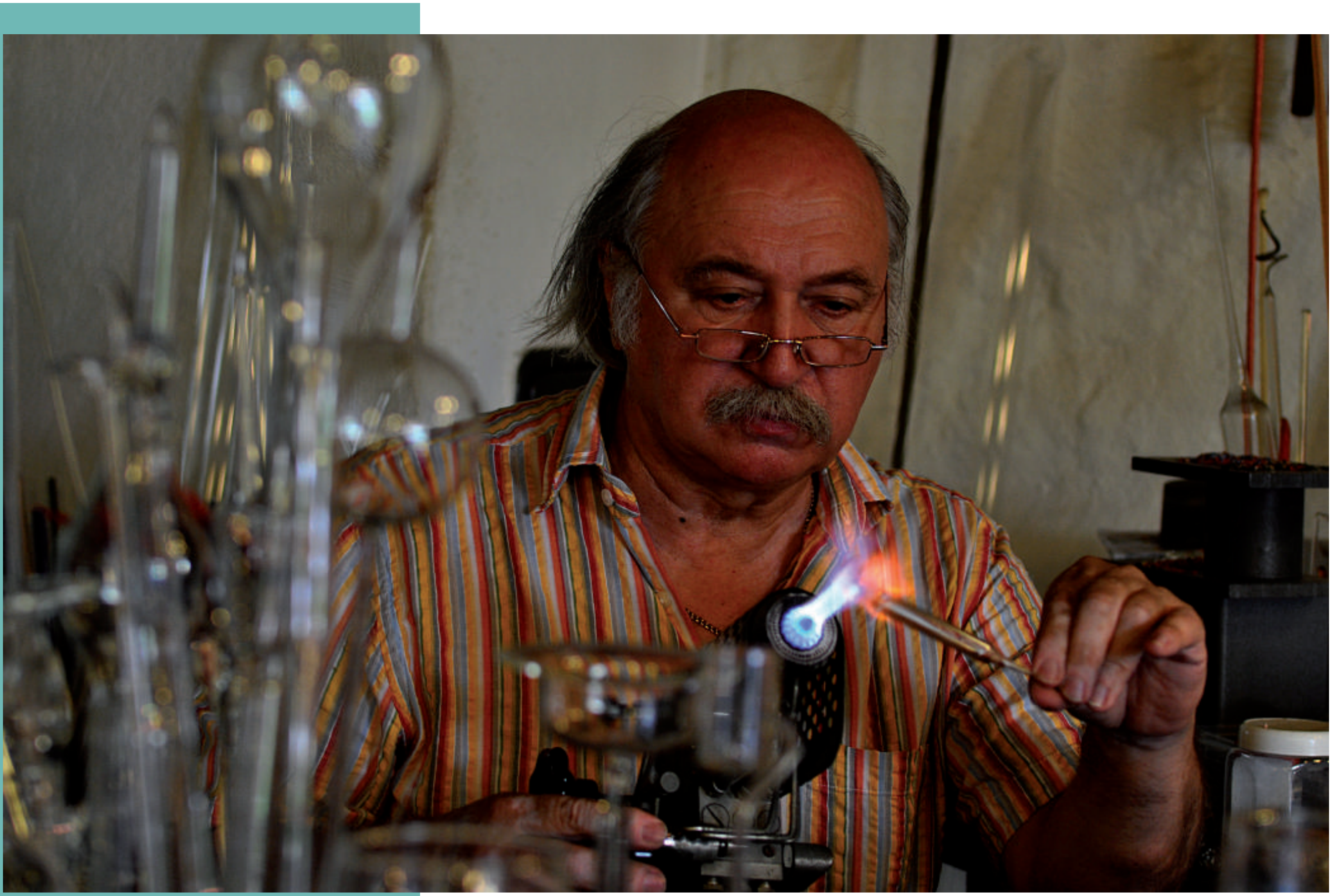


Figure 2.9. Lampworking, used both by the scientific and arts communities for secondary processing.
Source: Pixabay.

such technology, only subsequently to move to solid state electronics. The key property of glass was that it could hold a high vacuum over many years but also that a leak tight electric connection to the outside could be achieved. This required an understanding of the thermal expansion behavior of both metal and glass.

In the middle of the 20th century, as the load on the hard-wired electrical telephone increased, scientists begin to question the possibility of encoding electrical signals into a light beam and using the transparency of glass for transmission over long distances. This led to widespread use of glass products in the communications and electronics industries as described in Chapter 5.

Glasses and education

Education is central to the progress of our society and links closely to the storage of knowledge. Both are at the heart of the International Commission on Glass (ICG) and are considered in Chapter 11.

Shaping the world through glass artists/museums

The Island of Murano, Italy is a go-to places for glass art, and its economy is heavily reliant on artefacts whose price can range from a few to many thousand dollars. But rich and developing countries alike now and throughout history have had businesses making and selling glass souvenirs of local tourist attractions and producing beautiful glass objects such as beads, necklaces, earrings, even cuff links as well as glass sculptures and decorated windows for churches, gardens and public places. Indeed, international trade in glass beads was already widespread several millennia ago. The equipment needed can be less sophisticated than for other areas of glassmaking and may be accessible to the amateur community. For example, sea glasses, unlike plastic waste, are prized by beachcombers; created by the incessant tumbling action of waves on discarded glass fragments, their rounded shapes with translucent delicate colors are much appreciated for jewelry. The Studio Glass movement, whose 60th anniversary is in 2022, is but one vibrant area within this picture. These subjects are expanded in Chapters 9 and 10.

Summary

With its unparalleled versatility and technical capabilities, glass has fostered numerous cultural and scientific advancements. Its history is shared with the evolution of humankind. Its future will contribute to the challenges of a sustainable and fairer society. Let's drink a glass to that!

Further reading

BONTEMPS, G. (2008): *Guide de Verrier: Bontemps on Glass Making* (translated by M. Cable), Society of Glass Technology.

DEUTSCHES MUSEUM (n. d.): *Glastechnik* (1-5): Vol 1. *Glass: The Material*; Vol 2. *Glass Holloware*; Vol 3. *Flat Glass*; Vol 4. *Speciality Glass*; Vol 5. *Lampworking, Scientific Glassblowing.*

GAN, F.; LI, Q. & HENDERSON, J. (2016): *Recent Advances in the Scientific Research on Ancient Glass and Glaze*, World Century Publishing Corporation.

NERI, A. (2001): *The Art of Glass* (translated by Christopher Merrett and edited by M. Cable), Society of Glass Technology.

VANDERSTUKKEN, K. (2016): *GLASS. Virtual, Real*, Black Dog Publishing.

JULIAN R. JONES AND DELIA S. BRAUER

3. Glasses for Healthcare

Introduction to the types of glasses used in healthcare

When glass is selected as the optimal material for a particular application, it is usually chosen for its transparency and optical properties, or for its ability to resist corrosion. In healthcare, these types of glasses are still very important, but another, more unusual type of glass is also used, which is designed to dissolve or "biodegrade". Bioglasses are unique materials that can actively promote healing of tissues, such as bones or skin lesions, and they have thus changed the way clinicians think about biomaterials. They can also kill bacteria where antibiotics have failed.

"Conventional" glasses and "bioglasses" all play important roles in healthcare, some impacting our lives daily, others enabling lifesaving or life changing surgery. This chapter will begin discussing the application of traditional glasses in healthcare provision before moving to bioglasses in regenerative medicine.

Inert glasses

We are all familiar with eyeglasses, or spectacles, which a long time ago revolutionised the quality of life of our ageing population by enabling us to see clearly when our own lenses have deteriorated. Nowadays, many people of all ages, including small children, wear glasses to help them see better. The social and economic impact of eyeglasses is far more difficult to imagine, but it is clearly global and invaluable. Glass lenses work by bending light to a focal point, correcting our vision. Optical fibres, like those used in high-speed data

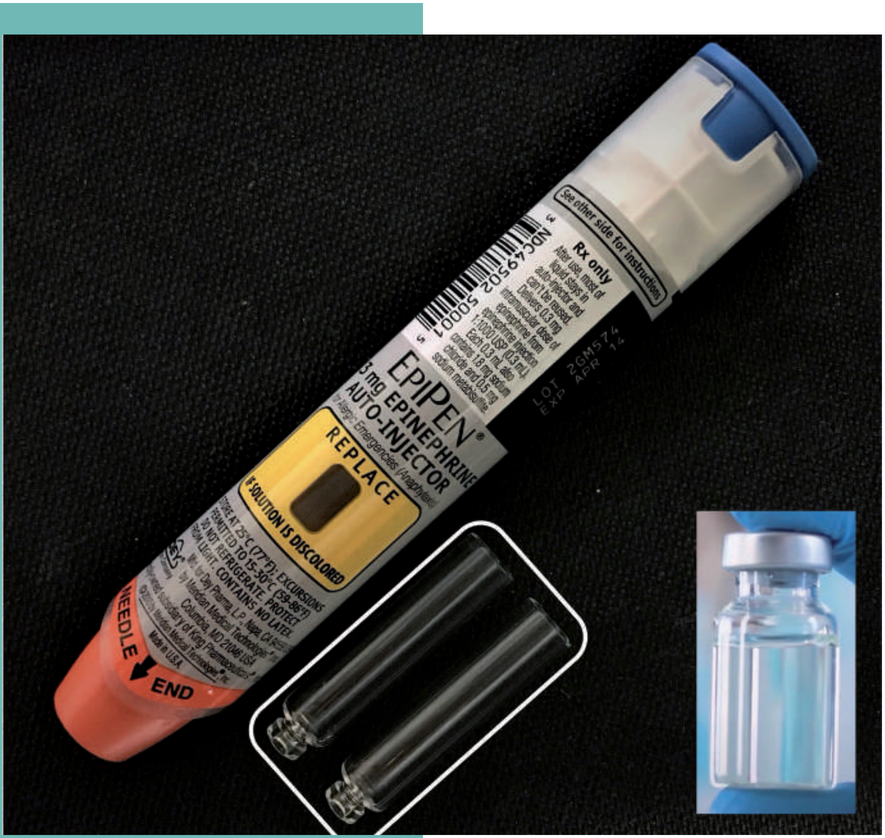


Figure 3.1. An EpiPen® with its chemically toughened glass cartridges (white box); inset: a vaccine vial.

Source: EpiPen® courtesy of Saxon Glass Technologies (US); inset courtesy of GIMAV/VITRUM (Italy).

transfer such as fast broadband internet, also work by bending light. Those same fibres are used in keyhole surgery and endoscopic diagnoses. The thin glass fibres enable surgeons to see clearly around corners to carry out procedures through very small incisions. This not only reduces scarring but also the chance of infection. The flexibility of the fibres means clinicians can insert the arthroscope in a safe entry point, such as the thigh, and navigate their way to the critical organ where to perform surgery, including life-saving heart surgery.

Another serious risk to life is severe allergies that can cause anaphylaxis and fatal collapse of upper respiratory tracts. Approximately 20% of the European population suffer from chronic allergies, and another million people are estimated to have allergies unbeknown to them which can develop at any time. Commonly known by a brand name "EpiPen®" (Figure 3.1), syringes can rapidly administer a dose of life-saving adrenaline (epinephrine). The action of injection is a jab into the upper thigh, usually through layers of clothes, as rapid administration is critical in severe cases. This requires not only a high-strength needle but also a shatterproof cartridge that contains the drug (Figure 3.1). The cartridges are made of borosilicate glass for its chemical stability, so it does not alter the chemistry of the drug, but conventional borosilicate glass would shatter in about 10% of applications. The use of high-strength chemically toughened glass, made using a process similar to chemically tempered cover glass production for mobile phone screens, means that fracture is almost impossible when the EpiPen® is used.

At the time of writing, the world is suffering a global pandemic where efficacy, safety and distribution of vaccines have been in the spotlight.

Figure 3.2. Mirragen® cotton-like glass for healing chronic wounds.
Source: ETS Wound Care, MO, USA.

Like many pharmaceuticals, vaccines contain sensitive molecules that must be kept in containers which preserve them and do not interact with their contents. Corrosion-resistant borosilicate glasses are the material of choice for COVID-19 vaccine vials, and chemical strengthening can ensure minimal loss of their valuable cargo. Increasing vial production without reducing quality or quality control was one of the many challenges during the early stages of the pandemic.

Another serious medical condition that afflicts a large proportion of the global population is diabetes. While the glucose level in the blood can be regulated through insulin injection, diabetic patients live with other effects of their condition, such as inhibited wound healing. Skin wounds take longer to heal for diabetic patients, often not healing at all. Glasses can help here, too, as we will see below.

Bioglasses

Bioglasses are not corrosion resistant, but rather they are designed to undergo safe dissolution inside the human body, assisting with the body's natural repair mechanisms.

Chronic wounds are those that do not heal under conventional treatment, and they are a serious problem as open wounds are prone to infection. Chronic wounds are more common in diabetic patients, due to disruption of the multi-stage wound healing cascade, impaired blood vessel development in the wound for example. If infection takes hold, it can ultimately lead to amputation. A medical device called Mirragen® (ETS Wound Care, US) has been shown to heal chronic wounds in diabetic patients [1], including venous ulcers with yeast infections that had not healed during many months of conventional treatment. Consisting of spun borate-based glass fibres (Figure 3.2), Mirragen® has the appearance and flexibility of white cotton candy. The bundles of fibres are inserted into the wound before a more conventional barrier dressing is applied on top. The fibres biodegrade in a matter of days, but during that time they provide their dissolution products of borate and calcium ions to the wound bed.

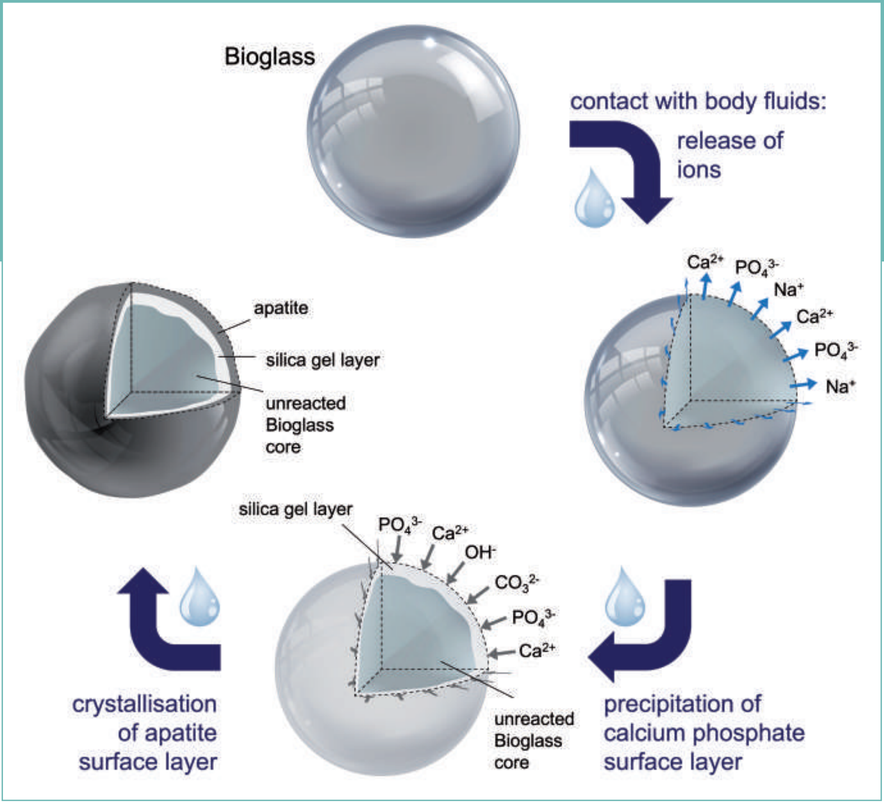


Figure 3.3. Schematic of Bioglass reactions with water.
Source: P. Wiemuth, University of Jena.

The ions seem to kill some pathogens and actively stimulate wound healing, most likely by accelerating angiogenesis (sprouting of blood vessels). However, the morphology of the fibres is also likely to play a role in accelerating the wound healing process, as the fibres have similar diameters to the collagenous extracellular matrix of skin. They can act as a framework (scaffold) for migration of cells, which may well have been dormant, into the wound bed. When the dressing is replaced after a day or two, the fibres will have biodegraded and a new matt of Mirragen® fibres can be placed into the wound.

The concept of a glass's dissolution ions activating cells was established more than a decade before they were used in wound healing in studies designed to understand the mode of action of the original "Bioglass®" in bone regeneration. The name "Bioglass" specifically refers to the first bioactive glass composition invented by Larry L. Hench in 1969 [2]. It was a silicate glass of the composition 46.1 mol% (45 wt%) SiO_2, 24.4 mol% Na_2O, 26.9 mol% CaO and 2.6 mol% P_2O_5, later termed 45S5 Bioglass. This composition was Hench's first attempt at making a glass that might bond with human bone. Amazingly, it worked. His clinical colleagues tested it in animal studies and found that it bonded to bone so well that it was difficult for them to remove it to be able to study the bonding! This changed the way clinicians thought about biomaterials, as previously biomaterials were selected from materials that were corrosion resistant, such as titanium alloys, high density polymers and alumina-based ceramics. If an inert (and sterile) piece of window glass was implanted next to a patient's damaged bone, it would be encapsulated by fibrous tissue and sealed off from the rest of the body by the immune system dealing with this foreign object. When a Bioglass implant comes into contact with blood, it undergoes surface dissolution, releasing calcium, phosphate and soluble silica (Figure 3.3). Bonding with damaged bone occurs because a bone mineral-like calcium phosphate layer forms on the surface of the glass [2]. As it is so similar to bone mineral, the cells of the body's immune system do not see it as foreign, so fibrous encapsulation does not occur. As this calcium phosphate layer grows, it integrates with collagen fibrils of the damaged host bone and is incorporated into the healing bone. The effect of the dissolution ions was discovered when Hench, his co-workers, and the company wanting to market Bioglass at the time (NovaBone Products, US), started to investigate why Bioglass worked so well in terms of encouraging high quality bone repair. In cell culture experiments, they found that the dissolution products, particularly silica species and calcium ions, stimulated human bone cells at the genetic level to produce more bone matrix [3].

Figure 3.4. Bioglass products for orthopaedic applications: NovaBone particulate (left), BonAlive granules (top right) and BonAlive putty (bottom right).
Source: Julian R. Jones.

We are now celebrating more than 50 years of its invention, although many fewer years of clinical use. The original 45S5 Bioglass has been implanted in more than 1.5 million patients who were suffering from bone defects, usually as a result of surgery removing abscesses or tumours, but sometimes due to fractures not healing by conventional treatments. In these clinical applications, Bioglass as a "medical device" is usually a white powder in a sterile and hermetically sealed sachet (Figure 3.4). Surgeons tend to blend the microparticles with blood, and once the blood begins to clot, the mixture can be pressed into the hole in the bone.

Since bioglass particulate was launched to market, several rival products have been released, such as Biogran (Orthovita, US), Unigraft® (Unicare Biomedical, US), GlassBone (Noraker, France), which are alternative 45S5 Bioglass products, and BonAlive®, which has the S53P4 composition (53.8 mol% (53 wt%) SiO_2, 21.8 mol% CaO, 22.7 mol% Na_2O, 1.7 mol% P_2O_5, BonAlive Biomaterials, Finland).

Most have been used in a similar manner, but BonAlive® has also shown benefits in patients with deep bone infections, known as chronic osteomyelitis. The infections are termed

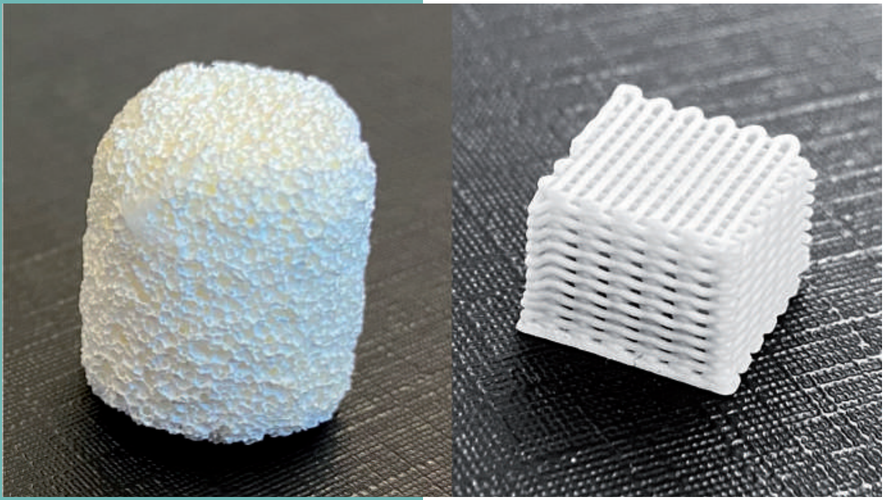


Figure 3.5. Photographs of bioactive glass scaffolds: a sol-gel foam scaffold that mimics the pore architecture of porous bone (left) and a 3D-printed scaffold (right).
Source: Julian R. Jones.

"chronic", as they are not responding to treatment by antibiotics alone. However, when the bioactive glass was implanted into the bone (along with the antibiotics), the infection subsided [4]. These findings are particularly important as many bacteria are becoming resistant to existing antibiotics.

Glass particles alone can be difficult to handle, therefore many orthopaedic clinicians prefer to use bioactive glass in the form of a putty. So, putties have been developed consisting of polyethylene glycol (PEG) carriers packed with Bioglass that can be delivered using syringes (Figure 3.4). When bioactive glass particles are used to repair bone defects, they act as steppingstones, encouraging the bone to cross the gap before they biodegrade. For many bone defects, a more robust three-dimensional template (scaffold) is needed to act as a framework for bone growth. Importantly, the pores must be open to allow bone and blood vessel ingrowth. However, producing a porous scaffold from the original Bioglass is challenging, because the conventional strategy for making a porous architecture from a glass or ceramic would be to sinter particles together and heating Bioglass to the temperature required for sintering causes crystallisation [5]. There are two ways to prepare bioactive glass scaffolds that do not crystallise: altering the glass composition to one that does not crystallise or using the sol-gel process. Adding more components into the glass composition can increase the crystallisation temperature, thereby opening the processing window, and thus allow for sintering without crystallisation occurring. Figure 3.5 shows photographs of bioactive foam and 3D-printed bioactive scaffolds. The foam structure mimics the architecture of porous bone and can be created using vigorous agitation with surfactants, either by foaming glass particles in a water-based slurry prior to sintering, termed gel-cast foaming [6], or by introducing a foaming step into the sol-gel process [7].

The sol-gel process forms the silicate network through chemical synthesis, wherein nanoparticles form in solution and assemble as covalent bonds form a gel. The gel is usually heated to drive off the water, which leaves a nano porous glass of large surface area. As the sol-gel process does not involve melting, sodium, which lowers the glass melting temperature, is not required in the composition, so the bioactive glass compositions can be more simple [8]. Foamed sol-gel and gel-cast foam scaffolds both result in spherical pores connected by circular interconnects or pore windows. Those 'windows' are key for 3D bone ingrowth.

Glass powders can be 3D-printed if they are mixed with a binder, or carrier gel, that can undergo shear thinning [9]. The grid-like 3D structure can provide high strength in compression, similar to that of dense bone, while maintaining pore channels suitable for vascularised bone ingrowth (Figure 3.6b). Direct comparison of bone regeneration in foam and 3D-printed scaffolds was performed in a rabbit model. The pore window (interconnect diameter or channel width) were matched, at just over 100 µm, which meant the foam had a much higher total porosity than the printed scaffold (Figure 3.6a,b). At 11 weeks in vivo, the foam scaffold had biodegraded and the defect filled with new bone (Figure 3.6c), while the 3D-printed scaffold remained (Figure 3.6d). However, the bone growing through the 3D-printed scaffold was of higher density and could therefore be considered of higher quality, while the rapidly formed bone in the defect with the foam implant was similar to that of the control. A degradation time of 11 weeks may be too rapid in a human patient, so the 3D-printed scaffolds may be preferred. Despite their promise, porous bioactive glass bone scaffolds have yet to make it to clinical use.

Perhaps surprisingly, bioactive glass has had an even greater impact in consumer healthcare. The largest commercial use of bioactive glass, and perhaps any bioactive biomaterial, is in toothpaste designed to treat hypersensitivity of teeth (Figure 3.7a). While many of us know the sharp pain one can feel when biting into cold ice

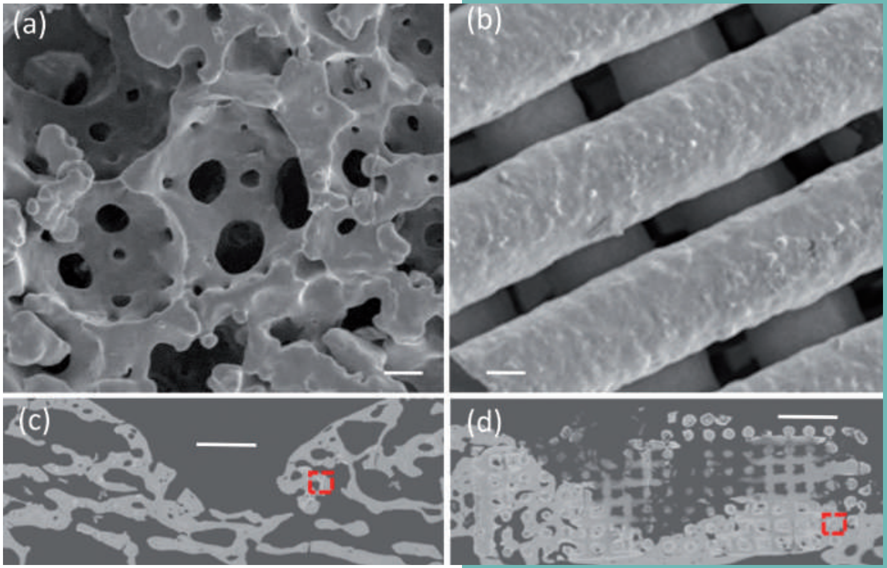


Figure 3.6. Comparing bone regeneration in a rabbit between foam and 3D-printed bioactive glass scaffolds of similar pore channel sizes; scanning electron microscopy images: (a) interconnected pores in the glass foam, scale bar = 100 µm, (b) pore channels in the 3D-printed scaffold, scale bar = 100 µm; (c,d) new bone formation at 10 weeks after implantation of (c) the foam and (d) the 3D-printed scaffold (scale bar = 1 mm). The red boxes show examples of new bone formation.
Source: Modified from Shi *et al.* [10].

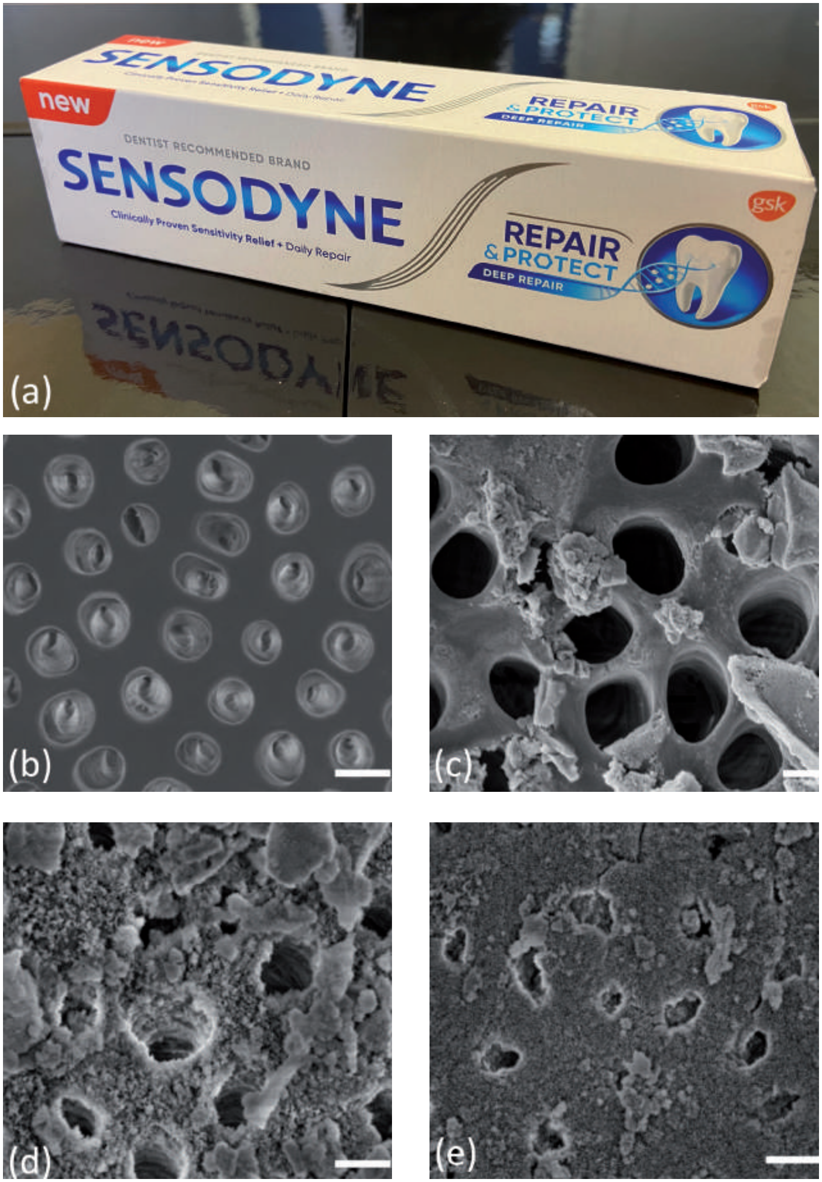


Figure 3.7. (a) Photograph of Sensodyne Repair and Protect toothpaste packaging, which contains NovaMin®, fine Bioglass particules; and (b-e) scanning electron microscopy images of tooth dentin [11] (bar = 1 μm): (b) untreated, (c) immediately after application of Bioglass in artificial saliva; (d) 24 h after Bioglass application; (e) 5 days after application.
Source: (a) Julian R. Jones; (b-e) modified from Earl *et al.* [11].

cream or taking a sip from a hot cup of coffee, for many the pain is chronic and needs treatment. The pain is thought to be caused by exposed tubules in our dentine (Figure 3.7b). Our teeth are covered by hard enamel, underneath which is the dentine. Enamel and dentine are very similar to bone, in that they contain calcium phosphate mineral and collagen, and the tubules in the dentine lead to the nerves in the pulp chamber in the heart of the tooth. Early toothpaste for hypersensitivity delivered anaesthetics during brushing, but now toothpastes have been developed that can occlude the tubules by promoting formation of new calcium phosphate mineral. This occurs because the bioactive glass dissolves in saliva, releasing calcium and phosphate [11]. As saliva is already rich in calcium phosphate, saturation occurs, and this natural mineral is deposited on the surface of the teeth (Figure 3.7c,d).

The first bioactive glass to be used in toothpaste was the 45S5 Bioglass composition. As fluoride is known to be greatly beneficial for remineralising

Figure 3.8. Application of a dental inlay made from a leucite glass-ceramic: (a) initial amalgam filling, (b) preparation of the molar for inlay restoration, (c) final state after adhesive luting and polishing of the inlay.

Source: Ritzberger *et al.* [13] (CC BY 3.0).

teeth, a new fluoride-containing bioactive glass composition, BioMin® F (BioMin Technologies, UK), is now on the market. It releases fluoride ions in addition to calcium and phosphate when in contact with saliva, resulting in a tooth mineral that is less likely to dissolve in acids, for example when we consume lemonade or fruit juices.

Bioglass is also used in several cosmetic creams, particularly as Vitryxx® (Schott AG), a very finely ground particulate. Vitryxx is thought to have anti-ageing benefits, such as reducing redness and wrinkles.

Glass-based materials in dentistry

When glass is heated above a certain temperature, it crystallises, forming a glass-ceramic. Glass-ceramics can show interesting combinations of properties, such as transparency and high strength. We know them for example from cooker tops, where they can survive drastic changes in temperature without shattering. In the field of dentistry, glass-ceramics are used with great success to replace teeth [12], as they are strong enough to withstand the forces during chewing and can be made to look just like natural teeth. They are also chemically durable and survive constant exposure to saliva, low pH during the drinking of juices or changing temperatures when we eat ice cream or drink hot beverages. Glass-ceramics are used to make dental inlays, crowns and bridges, and often consist of a combination of different glass-ceramics. For example, lithium disilicate is strong enough to be used as the main framework in bridges, while leucite or fluorapatite glass-ceramics give the appearance of natural tooth (Figure 3.8).

But even in dentistry soluble glasses are used. A certain type of glass that contains aluminium ions, referred to as

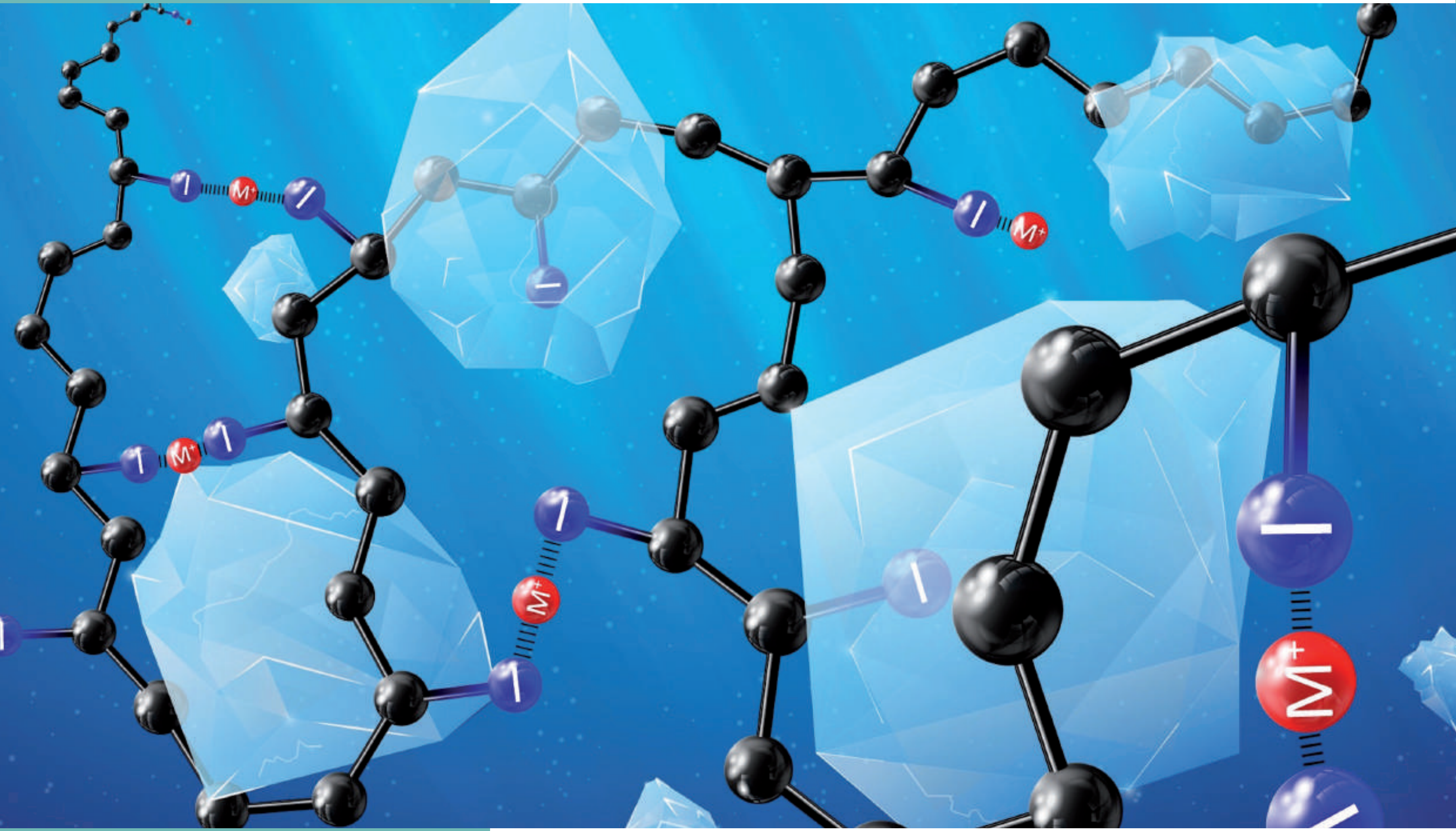
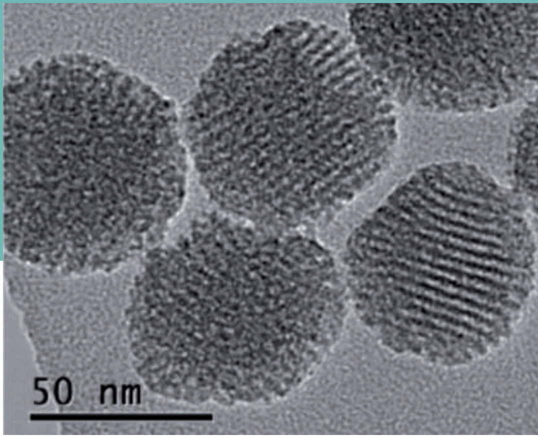


Figure 3.9. Schematic of the atomic structure of a set glass ionomer cement: ionic cross-linking between functional groups (e.g. carboxylate groups; blue) attached to polymer chains (black) and metal cations (red).
Source: P. Wiemuth, University of Jena.

aluminosilicate glass, can dissolve rapidly when in contact with acids. When a fine powder of such a glass is mixed with an acidic polymer, for example poly(acrylic acid), the glass dissolves and releases ions such as aluminium and calcium. These ions then bond to the polymer, and together ions and polymer form a strong cement (Figure 3.8). These cements, called glass ionomer cements [14], have been used in dentistry for several decades now to treat minor cavities, as adhesives ("glue") or as sealants to prevent new caries forming in the grooves (fissures) on the top of our teeth. As the glass used also contains fluoride

Figure 3.10. Transmission electron microscope image of nanoporous silica nanospheres that can be loaded with chemotherapy drugs and functionalised with molecules that can target specific cancer cells.
Source: Modified from Chen *et al.* [16].



ions, glass ionomer cements also release fluoride and help to prevent caries. Glass ionomer cements are used regularly by dentists, and most of us have this material somewhere in our teeth. One great advantage of these glass ionomer cements is that for setting they do not require special equipment such as UV light. So, they can be used easily even in rural areas of developing countries, helping dentists to bring dental care even to remote spots.

Therapeutic nanoparticles

While not really considered a bioactive glass, radioactive glass spheres are used to treat liver cancer, whereby they are injected into the blood stream, become lodged in the liver and emit radiation from inside the liver to destroy the tumour. They are used when externally applied radiation is not effective. There are many experimental cancer treatments that use nano-porous glass nanospheres (Figure 3.10) that aim to deliver chemotherapy drugs only to the cells that are targeted. It is well known that conventional chemotherapy has drastic side effects, which is due to it killing useful cells at the same time that it kills the cancer cells. Silica nanoparticles can carry the drug inside the pores and the particles are small enough that they can be made to pass by cells without interacting with them so they only interact with the target cancer cells [15]. Then, the cancer cells take them in and when they are inside, they release their cargo. Once the efficacy of the targeting is perfected, these strategies are likely to revolutionise cancer therapy.

While targeted chemotherapy is challenging to deliver, bioactive glass nanoparticles could also deliver therapeutic ions, for example nanoparticles delivering zinc ions were found to kill breast cancer cells without killing healthy equivalent cells [16]. Therapeutic benefits may extend beyond cancer. A disease that affects most of us as we age is osteoporosis, where the cells that take our bone away are working faster than the cells laying down new bone, resulting in loss of bone density.

Figure 3.11 shows bone marrow stem cells that have internalised bioactive glass nanospheres that are delivering strontium ions inside the cells. The combination of silica, calcium and strontium promoted stem cell differentiation down a bone pathway, whereas those that were given nanospheres without the strontium remained as stem cells [17]. The possibilities for bioactive glasses seem endless, but medical device companies have to prove every new device is safe and effective for each individual clinical application before they can used.

Summary

Biomedical glasses are key contributors to the Glass Age. Strong, corrosion resistant glasses enable storage and delivery of life saving medicines,

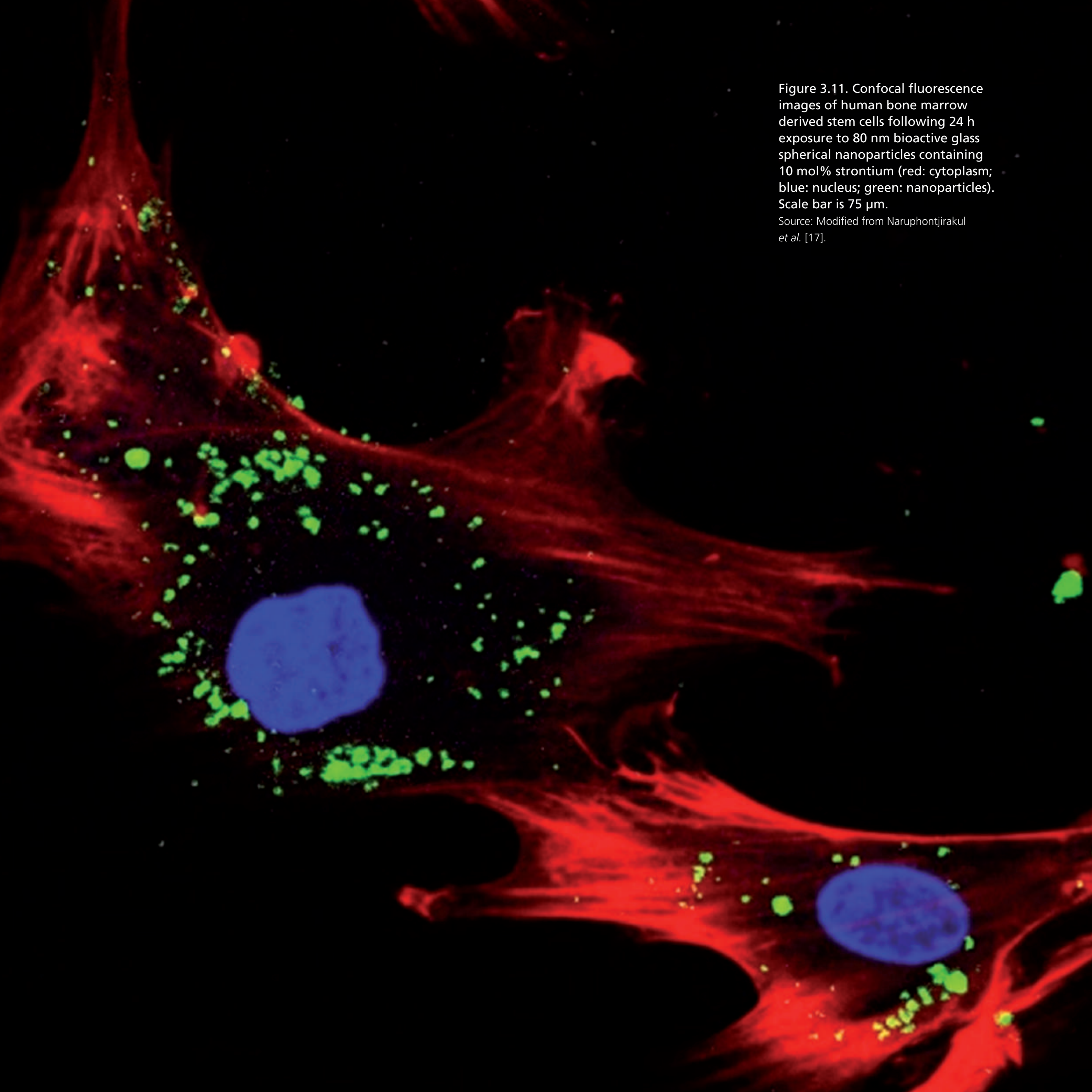


Figure 3.11. Confocal fluorescence images of human bone marrow derived stem cells following 24 h exposure to 80 nm bioactive glass spherical nanoparticles containing 10 mol% strontium (red: cytoplasm; blue: nucleus; green: nanoparticles). Scale bar is 75 μm.

Source: Modified from Naruphontjirakul *et al.* [17].

optical glasses allow for key-hole surgery. Glass-ceramics and glass ionomer cements are used to repair our teeth after caries damage. Bioactive glasses, which are designed to dissolve and biodegrade in the human body, have improved the quality of life for millions of patients, regenerating bone and skin faster and in some cases healing tissue that would not heal by any other means. The number of healthcare applications of glass will likely continue to increase in the future.

References

[1] Buck, D. W. (2020): "Innovative Bioactive Glass Fiber Technology Accelerates Wound Healing and Minimizes Costs: A Case Series", *Advances in Skin & Wound Care*, 33 (8).

[2] Hench, L. L. *et al.* (1971): "Bonding mechanisms at the interface of ceramic prosthetic materials", *Journal of Biomedical Materials Research*, 2 (1): 117-141.

[3] Xynos, I. D. *et al.* (2001): "Gene-expression profiling of human osteoblasts following treatment with the ionic products of Bioglass (R) 45S5 dissolution", *Journal of Biomedical Materials Research*, 55 (2):151-157.

[4] Lindfors, N. *et al.* (2017): "Antibacterial Bioactive Glass, S53P4, for Chronic Bone Infections - A Multinational Study" (81-92), in L. Drago (editor), *Modern Approach to Biofilm-Related Orthopaedic Implant Infections: Advances in Microbiology, Infectious Diseases and Public Health. Volume 5*, Springer.

[5] Chen, Q. Z. Z.; Thompson, I. D. & Boccaccini, A. R. (2006): "45S5 Bioglass-derived glass-ceramic scaffolds for bone tissue engineering", *Biomaterials*, 27 (11): 2414-25.

[6] Nommeots-Nomm, A. *et al.* (2017): "Highly degradable porous melt-derived bioactive glass foam scaffolds for bone regeneration", *Acta Biomaterialia*, 57: 449-461.

[7] Jones, J. R.; Ehrenfried, L. M. & Hench, L.L. (2006): "Optimising bioactive glass scaffolds for bone tissue engineering", *Biomaterials*, 27: 964-973.

[8] Li, R.; Clark, A. E. & Hench, L. L. (1991): "An investigation of bioactive glass powders by sol-gel processing", *Journal of Applied Biomaterials*, 2 (4): 231-239.

[9] Fu, Q.; Saiz, E. & Tomsia, A. P. (2011): "Bioinspired strong and highly porous glass scaffolds", *Advanced Functional Materials*, 21 (6): 1058-63.

[10] Shi, X. *et al.* (2020): "Bioactive glass scaffold architectures regulate patterning of bone regeneration in vivo", *Applied Materials Today*, 20: 100770.

[11] Earl, J. S. *et al.* (2011): "Physical and chemical characterization of dentin surface, following treatment with NovaMin® technology", *The Journal of Clinical Dentistry*, 22: 2-67.

[12] Höland, W. *et al.* (2006): "Clinical applications of glass-ceramics in dentistry", *Journal of Materials Science: Materials in Medicine*, 17 (11): 1037-42.

[13] Ritzberger, C. *et al.* (2010): "Properties and Clinical Application of Three Types of Dental Glass-Ceramics and Ceramics for CAD-CAM Technologies", *Materials*, 3 (6): 3700-13.

[14] Nicholson, J. W. (1998): “Chemistry of glass-ionomer cements: a review”, *Biomaterials*, 19 (6): 485-494.
[15] Ashley, C. E. *et al.* (2011): “The targeted delivery of multicomponent cargos to cancer cells by nanoporous particle-supported lipid bilayers”, *Nature Materials*, 10 (5): 389-397.
[16] Chen, S. *et al.* (2020): “Biodegradable zinc-containing mesoporous silica nanoparticles for cancer therapy”, *Materials Today Advances*, 6: 11.
[17] Naruphontjirakul, P. *et al.* (2019): “Human mesenchymal stem cells differentiate into an osteogenic lineage in presence of strontium containing bioactive glass nanoparticles”, *Acta Biomaterialia*, 90: 373-92.

HIMANSHU JAIN AND PENG SHOU

4. Affordable and Clean Energy Provided by Glass

Introduction

Glass plays a critical role in a broad range of energy technologies spanning energy generation, conservation and storage. In many cases, glass is the enabler of these technologies or a key component of devices. For example, in the energy generation sector photovoltaic (PV) and concentrated solar power applications cannot be realized without suitable glasses for protecting and packaging active devices. Glass is the most promising wasteform for containing and disposing high-level nuclear waste, thereby assuring that this mode of energy generation remains clean. In the form of foam, glass is a preferred choice over polymers for heat and sound insulation of buildings due to its low density, low thermal conductivity, incombustibility, adhesive compatibility, etc. In more advanced applications approaching commercialization, such as solid-state batteries for energy storage glass plays a more active role, performing specific functions within a device. In the following sections, we review six representative application areas exemplifying how glass is addressing one of the most pressing societal needs of today.

Glass for photovoltaic technology

As the world today sets carbon neutrality as the leading direction to go green and more than 120 countries have pledged to achieve this by the year 2050, the next 30 years represent a crucial window of opportunity. For this goal, we need to refocus on the energies we use as our

Figure 4.1. World's largest integrated thin-film solar cell building demonstration project in Anhui, China.
Source: China Triumph Engineering.

Figure 4.2. Photovoltaic panel.
Source: Pixabay.

power sources and develop new industries as the foundation on which to build the edifice of green development. To transform a fossil-based world to green energy, humankind will inevitably embrace cleaner and ever lower carbon energies. Ensuring energy supply and energy security, and enhancing the efficiency of energy production and consumption remain our basic tasks. It is evident that carbon neutrality will not be realized without renewable energies.

As an important constituent of renewable energies, photoelectric solar energy is becoming more important in the world's future energy system (Figure 4.1). According to China National Energy Administration, under the zero-carbon scenario by 2060, photoelectric power generation will reach 3414 billion kWh, amounting to roughly 30% of the world's power supply, thus constituting its main part.

Materials are key to propel the development of photovoltaic power generation. A silicon-based solar cell is usually composed of a cover glass, a film, some solar cell materials, special metal wires, a backplane glass, among others. The main body of the solar cell is sealed in the film between the cover and backplane glasses. In the field of thin-film solar cells, glass is the key substrate for film coating required by various cell types. Thus, glasses underpin the development of photoelectricity.

With the development of photovoltaic glass, silicon-based solar cells currently occupy a dominant position in photovoltaics, accounting for 93% of the global market in 2020 with a module conversion efficiency of roughly 25%. As photovoltaic glass becomes thinner and cell's conversion efficiency improves, the dual-glass module, tunneling-oxide passivating contact (TOPCon) heterojunction with intrinsic thin film solar cell (heterojunction technology, HJT) will define the development of the crystalline silicon solar cell.

Figure 4.3. PV energy landscape in the desert.
Source: Pixabay.

The second-generation photovoltaic, thin-film solar cells offer a lower production cost, less pollution, stable performance and good low light performance. Compared with crystal silicon solar cells, they are a perfect choice for building-integrated photovoltaics (BIPV). Due to persistent silicon raw material shortages in the international market and an ever-quickening pace to cut carbon emissions, thin film solar cells represent a new trend that is gaining considerable attention in the photoelectric market

Figure 4.4. 50MW Solar Thermal Power Plant in Qinghai, China.
Source: China Triumph Engineering.

(Figure 4.2 and Figure 4.3). At present, industrial thin-film solar cells, such as those based on cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), have a module conversion efficiency around 20%. The progress in their efficiency enhancement has outpaced that for crystal silicon solar cells. Thanks to the application of thin film solar cells in the construction industry, BIPV has become a high-growth area around the world, especially in developing countries. As China steps up efforts to formulate its national standards of thin-film solar cells for BIPV, the importance of glass in photovoltaic application will be further highlighted.

Glass for solar-thermal technology

The Sun with its effective blackbody temperature of 5762 K steadily emits radiant energy, of which about 1.8×10^{14} kW is intercepted by the Earth. This solar heat, captured directly or indirectly, provides the most abundant of all renewable sources of energy available for human use. Solar thermal utilization dates back to prehistoric times and it can be used extensively. Basically, photothermal conversion materials are used to convert solar radiation into thermal energy, which can then be used in industrial productions, agriculture, animal husbandry and other fields. As science and technology advanced, solar thermal utilization has expanded from low temperature applications (<100ºC) to medium and high temperature applications (≥100ºC). New technologies such as solar thermal power generation (Figure 4.4), solar stills for water purification and distillation, integrated solar buildings and thermochemical hydrogen production have been developed in recent decades to provide clean energies of higher-grade.

The key technologies for solar thermal utilization are heat collection, transmission and storage, and new glasses play a critical role in all three. In heat collection, the core component is the concentrating reflector, composed mainly of ultra-clear glass (also known as low-iron glass). The concentrating reflector is normally composed of a 1 mm to 4 mm ultra-clear glass substrate coated with a reflective silver layer, protected with a layer of copper and several protective paints on the back. For a concentrating reflector, reflectance can increase by 1.5% for every 1% increase in glass transmittance. Thanks to continuous optimization of raw material formulation and furnace structural design as well as fine control of the melting process, ultra-thin and ultra-clean glass with high transmittance and high weather resistance can be produced, paving the way for high-quality heat collection and highly efficient thermoelectric conversion.

Additionally, in heat transmission, the inner metal tube coated with a medium-high temperature selective absorption coating is sealed in a borosilicate glass tube with good acid and water resistance and a well-matched coefficient of linear expansion to the metal phase, bringing in a medium-high temperature solar vacuum tube collector with an operating temperature up to 400°C —a temperature that ensures more stable and efficient transfer and utilization of solar heat. In heat storage, by adding transparent phase-change materials to the glass envelope, the newly developed glass curtain wall can utilize solar energy effectively and reduce energy consumption of buildings. It is critical to the development of ecological architecture and the realization of a carbon neutral strategy. Therefore, new glass materials remain the basic component to enable efficient utilization of solar heat.

Highly efficient use of solar heat is an important aspect of solar energy utilization. Thanks to continuing R&D efforts, new glass materials are increasingly used in solar heat. Undoubtedly, the development of these new materials and technologies will bring new opportunities and challenges to the solar thermal industry, nurturing economy of scale, accelerating commercialization, and promoting

Figure 4.5. Wind Farm.
Source: Pixabay.

Figure 4.6. A stunning image of a wind turbine.
Source: Pixabay.

the rapid development of global renewable energies and low-carbon economies.

DESERTEC is an international project at Noor Ouarzazate in Morocco to provide sustainable wealth for every human on earth. The DESERTEC Foundation aims to turn the biggest idea of the 21st century into reality: green Desert-Energy that advances the decarbonization of Europe, guarantees Africa clean prosperity and makes the Middle East independent of oil income. As bad as deserts are for food production, they are ideal for energy production. At no other place in the world does the sun shine as much and so many strong winds blow across their flat plains. French and German companies are interested and China has also joined the project. The new 200MW Noor II plant has the world's largest installed capacity as a parabolic trough concentrated solar power plant, while the 160MW installed capacity of Noor III is the largest amongst the world's concentrated solar power plants.

Glass for windmill turbines

Wind, nature's gift to mankind, is inexhaustible and readily available. When Charles F. Brush built the world's first wind turbine in 1887, a new chapter was opened in wind power generation history. In the early days, blades of wind turbines were made of cedar wood. The improvement of wind

Figure 4.7. Used nuclear fuel is stored above ground in massive airtight steel or concrete-and-steel dry canisters, or in steel-lined water-filled concrete pools.

Source: https://www.energy-northwest.com/energyprojects/Columbia/Pages/Used-Fuel.aspx

power generation required lighter, higher-performance and lower-cost turbine blades. With seminal developments in glass melting, fiber forming, glass formulation and other related technologies, glass fibers with high-strength and high-modulus could be manufactured. These new developments led wooden and metal blades of wind turbines to be replaced by glass fiber composites such as seen in Figure 4.5 and Figure 4.6. High-performance glass fiber-reinforced polymer composites have excellent mechanical properties, processability and corrosion resistance. They can meet the needs of large-scale marine application of wind power and have become the material of choice for large-sized wind turbine blades.

At present, the world's total installed capacity of wind power is 743GW, accounting for 6% of global power generation. As the world strives to achieve carbon neutrality by 2050, shifting to sustainable sources of energy has garnered increasing attention from countries around the world. The world's energy pattern will also be reshaped, meaning the proportion of renewable energy such as wind in the total energy mix will only increase. To achieve "net zero" carbon dioxide emissions by 2050, the annual demand of 180GW of new wind power installed capacity and more than 30% of wind power generation in the total energy mix by 2050, will set off explosive growth of the wind power market. The demand of 10,000 to 15,000 tons of glass fiber for 1GW of wind power installed capacity will also prompt the glass fiber industry to innovate.

The future is in the hands of materials. Thanks to the continuous R&D of high-strength, high-modulus glass fiber and the strong demand for super-sized wind turbine blades, the performance of wind turbines will reach unprecedented levels. This will prompt the wind industry to reach price parity sooner with traditional fossil energy, thus demonstrating directly the value of clean and environmentally-friendly energy. Wind power will make our sky bluer and cleaner, and make us healthier, happier and live better. Figure 4.5 shows an eolic park (wind farm) by the coast and Figure 4.6 a giant wind turbine.

Glass for nuclear waste disposal

More than 250,000 metric tons of high level radioactive wasteform (HLW) from nuclear power plants and weapons production facilities worldwide, are under storage in tanks such as seen in Figure 4.7. Even though a small fraction of total radioactive waste, it contains much of the radioactivity, posing great danger for society and a challenge to scientists and engineers. This wasteform is waiting to be converted into solids and then disposed of permanently in geological repositories. The solidified wasteform with radionuclides immobilized in a suitable matrix must remain stable against corrosion from groundwater for 1000 years, when the radioactivity would become comparable to acceptable ambient conditions. Three immobilization technologies, viz. cementation, bituminization and vitrification have been demonstrated to be commercially viable. Among them the highest degree of volume reduction and safety are demonstrated by vitrification although it is the most complex and expensive method. After considerable analysis of pros and cons of various choices, glass has appeared as the material of choice, and vitrification of HLW is currently being practiced in Belgium, France, Germany, India, Japan, Russia, UK and the USA.

Glass is attractive to immobilize HLW waste through vitrification for the following reasons:

- Strong capability to immobilize reliably a wide range of elements including radionuclides.
- Relatively high loading of HLW thereby resulting in small volume to be disposed.
- High chemical durability if and when the wasteform comes in contact with natural waters.
- Desired properties have a high tolerance to radiation damage.
- Well established production technology that can be adapted from glass manufacturing.

Historically, borosilicate glasses were identified as potential hosts due to their high chemical durability, glass formability with HLW added as variety of oxides, and manufacturability. Subsequently, Russia focused also on sodium aluminophosphate glass as the HLW matrix. Overall, these glasses may contain more than 25 components. Such variations of composition, not to mention other test variables, have generated a plethora of data, making a comparison of relative performance very difficult. To overcome this challenge and establish a scientific basis for further developments, a six-component borosilicate glass known as the International Simple Glass (ISG) has been established by broad consensus to balance simplicity vs. similarity to waste glasses: $60.2SiO_2$-$16.0B_2O_3$-$12.6Na_2O$-$3.8Al_2O_3$-$5.7CaO$-$1.7ZrO_2$ (in mol%). Its basic properties and structure have been determined as a reference. In spite of considerable data generated on this and several other candidate glass compositions uncertainty remains about the assurance that overall a HLW package can maintain integrity over the lifetime of radioactivity under the highly interactive environment of radiation, temperature and groundwater. For example, new modes of corrosion of stainless steel have recently been identified at the interface with glass. Such enhancement of overall package degradation would require further optimization of individual components including glass.

Glass for photobioreactors

Photosynthesis by microalgae offers: an attractive approach to production of biomass rich in lipids and carbohydrates that can be used as a biofuel; CO_2 bio-fixation to reduce greenhouse gases; and treatment of wastewater to reduce

Figure 4.8. A photobioreactor made by Varicon Aqua for microalgae production; tubes are made of borosilicate glass.
Source: Courtesy of Akihiko Kanamoto, OP Bio Factory Co., Ltd, & Varicon Aqua.

excessive discharge of nitrogen and phosphorus that cause eutrophication. A suitable microalga can also produce bioelectricity in microbial fuel cells, and hydrogen for use as a pollution-free fuel. For an efficient production of microalgae for any of these applications with low probability of contamination, photobioreactors such as seen in Figure 4.8 are required. These closed systems offer desired control of the algae production process. Ideally, a photobioreactor system should allow control of: light penetration and distribution within the culture medium; CO_2 loading level; mixing and gas transfer; management of oxygen generated as a byproduct of photosynthesis process; temperature; pH; supply of nutrients; and hydrodynamic residence time.

The material requirements for the containment of microalgae within a photobioreactor system are to: (a) be chemically stable so that it does not corrode in salt water and can be cleaned and disinfected with commercial chemicals; (b) have a smooth surface and regular shape for uniform flow of medium to prevent biofilm formation; and (c) exhibit high transparency to sunlight yet be stable against ultraviolet wavelengths. Thin borosilicate glass tubes are shown to meet these requirements particularly well. Although such glass-based bioreactor systems require higher investment compared to those made from polymers like polyethylene or polyvinylchloride, their superior performance, low maintenance cost, and long life (>50 years) also make them economical over time.

Glass for energy storage technologies

Often there is a mismatch in the timing of energy production and its consumption in the required form. To resolve this mismatch, the energy must be converted into a form that can be stored for a period and then converted back into a form that can be utilized. The process of energy conversion should be sufficiently fast with minimal loss. Typically, electrical or thermal energy needs to be stored. The former is stored by converting it into a mechanical, chemical or electrochemical form, while the latter is stored through a change in material temperature, such as latent heat of phase change, or as thermochemical heat of change of a material's chemical structure. At present glass is not central to these applications in use today on large scale but is emerging as one of the most promising materials for future advancements. Examples for storing electrical energy include solid state batteries relying on electrochemical conversion and generating hydrogen relying on chemical conversion. In emerging batteries, glass is useful both as an ion conducting solid electrolyte and an electronic-ionic mixed conductor for electrodes. Hollow glass microspheres are proving to be a safe host for storing hydrogen that is produced by electrolysis of water. For storing thermal energy, the most widely used approach exploits phase change materials with large latent heat and then sensible heating of the melt of high specific heat. Here typical glass forming oxide melts are attractive over other salts due to their high characteristic energies and inertness towards metal containers.

Summary

The optical transparency to sunlight, high resistance to attack by chemicals and damage by radiation, versatility to dissolve high concentrations of extraneous oxides, and capacity for economic fabrication in complex shapes make glass indispensable to the realization of various energy technologies. Already, it is widely used in harvesting solar and wind energies via photovoltaics, solar-thermal, photosynthesis and windmill technologies. It is the material of choice for environmentally safe disposal of high-level nuclear waste that results from nuclear energy production. Further improvement in the performance of glass in these existing applications is expected with further optimization of compositions. Recent advancements in R&D have demonstrated proof-of-concept for applications of glass also in energy storage technologies such as solid-state batteries, hydrogen as a green fuel, etc., thus indicating tremendous opportunities alongside the challenges for growth of glass to address the problems of the energy sector.

References

Arinicheva, Y. *et al.* (2020): “Ceramics for electrochemical storage” (549-709), in O. Guillon (editor), *Advanced Ceramics for Energy Conversion and Storage*, Elsevier.

Brow, R. K. & Schmitt, M. L. (2009): “A survey of energy and environmental applications of glass”, *Journal of the European Ceramic Society*, 29 (7): 1193-1201.

Deubener, J. & Helsch, G. (2021): “Glasses for Solar-energy Technologies”, *Encyclopedia of Glass Science, Technology, History, and Culture*, 2: 1113-1123.

IAEA (2018): *Status and Trends in Spent Fuel and Radioactive Waste Management*, IAEA.

Konur, O. (editor) (2020): *Handbook of Algal Science, Technology and Medicine*, Academic Press.

Ojovan, M. I.; Lee, W. E. & Kalmykov, S. N. (2019): *An Introduction to Nuclear Waste Immobilisation*, Elsevier.

Schott (2017): “How using a PBR with high end glass components makes algae cultivation more economically viable”: https://pbr-blog.schott.com/2017/12/21/economic-efficiency-of-algae-cultivation

The Africa – EU Partnership (n. d.): “DESERTEC – tapping the solar power potential of the Sahara”: https://africa-eu-partnership.org/en/success-stories/desertec-tapping-solar-power-potential-sahara

Wind Energy and Electric Vehicle Magazine (2020): “Situation of wind energy in Spain and in the world”: https://www.evwind.es/2020/07/15/situation-of-wind-energy-in-spain-and-in-the-world/75762

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5. Glass in Information and Communication Technologies (ICT) and Photonics*

THE area of information and communication technologies (ICT) includes all technologies related to the accessing, retrieving, transmitting, manipulating and storing of information in a digital form. As such, ICT play a significant role in all aspects of present life. The rise of ICT in the last decades would not have been possible without two fundamental material groups: semiconductors (for laser diodes, and most notably silicon for computers and processing devices), and glasses (for optical fibers and photonic components). This Chapter provides a brief overview of the properties of various types of glass and of their applications to the development of optical fibers and photonic components.

Introduction

The 20th century has been described by many authors as the Electronic Age, due to the advent of electronic components, computers, and digital information. Silicon has certainly been the dominant material, with a large impact on the modern world economy.

The 21st century, on the other hand, may well be considered the Photonic Age, to recognize the vital role that light plays in our daily lives, from architecture to biology and medicine, not to neglect

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that internet communication, today a pillar of the global society, is only possible because of lasers and optical fibers. Not by chance, 2015 was celebrated by the United Nations as the International Year of Light and Light-Based Technologies. In this frame, one must also recognize the fundamental role that glass plays among the relevant materials for photonics. Glass is a complex material with unique properties, and technological demands now require greater use of its properties in relation to light, transparency being only the most common and most evident. Again, it is not by chance that the General Assembly of United Nations unanimously approved the resolution declaring 2022 the International Year of Glass.

This Chapter aims at briefly reviewing the role that glass (or, better, the many types of glass that the scientific research has synthesized and characterized) is playing in the generation, transmission and displaying of information.

Glass and optical fiber

Fiber optics represents a field of significant daily consequence where light and glass are intimately linked. Indeed, all modern means of communications and data / information technologies are enabled by hair-thin strands of glass that can carry light over hundreds of kilometers before needing (optical) signal amplification. The Internet, namely the word-wide system of connected computers and other electronic devices, already offers fast personal and business communications and access to information databases. There is, however, a continuous search for faster and higher capacity data technologies, with 5G being one upcoming solution. 5G, in fact, is the fifth generation of cellular networks, and promises to be up to 10 times faster than the 4G technology currently used by most cellular phones. The development of internet and 5G will require a further expansion of the fiber optic lines that will remain the data-transport backbone of the overall network. Presently, over 500,000,000 kilometers of communications glass optical fiber are manufactured globally each year, a remarkable indication of the importance of glass and light [1].

The history of fiber optics, particularly from a glass-perspective, is as intriguing as it is timely. For a fuller treatment of this synergy, the reader is referred to Ref. [2]. Briefly, it had long been appreciated that the use of light as a medium onto which information could be encoded was far superior to electricity from the standpoint of capacity (bandwidth). Considerable efforts were already underway in the 1950s concerning free-space optical communications and gas-filled or mirrored pipes as microwave guides. The conceptualization and construction of the maser, and, subsequently, its shorter wavelength sibling, the laser, further accelerated research into communications using visible or near-visible optical carriers. With a collimated and coherent light source in the laser, studies into waveguiding materials were an obvious complement. The pioneering realization that glass could enable suitably high transparency (low loss) fibers was made by Charles Kao, in 1966, for which he was awarded the 2009 Nobel Prize in Physics. In 1970, Corning won the race to fabricate the first < 20 dB/km low loss fibers by implementing a chemical vapor deposition (CVD) process enabled by a flame hydrolysis method developed there in the 1930s. Soon thereafter, consistent pioneering achievements in silica glass-based optical fibers, both passive and active, were made by Corning, Bell Labs, NTT, and the University of Southampton, among others, into the late 1980s. This period, from 1966 through to, about, 1990, represents a critical first phase of glass development for fiber optics.

By the early 1990s, optical fiber communication systems were beginning to be installed globally and materials efforts began to focus on glasses whose performance could exceed, at least in theory, that of silica. The most

Figure 5.1. The deposition section of a modified chemical vapor deposition (MCVD) lathe. The white glass is the porous silica soot deposited inside of a pure silica substrate tube prior to sintering and consolidation.

Source: Clemson University.

significant efforts focused on three thematic areas, predominantly driven by the growing needs for longer distance and higher capacity communication links: (i) ultra-low loss glasses, (ii) broadband optical amplifiers, and (iii) nonlinear glasses for low power switching and wavelength conversion.

Regarding ultra-low loss glasses and optical fibers, considerable effort focused on the development of non-oxide glasses, specifically chalcogenides and fluorides. Relative to SiO_2, weaker bonding and heavier atomic constituents in both these glass families lead to reduced vibrational energies. This causes absorption due to multiphonon processes to shift to longer wavelengths (lower frequencies), which leads to lower minimum intrinsic attenuation values than silica when Rayleigh scattering is considered (decreasing as (wavelength)$^{-4}$). A great many glasses and fibers in the ZrF_4- and InF_3-based fluoride systems, and As_2S_3, As_2Se_3, and Ga-La-S chalcogenide systems, were explored. However, while intrinsic ultra-low loss was possible, extrinsic losses, dominated by impurities in these melt-quenched glass systems, ultimately ended their consideration for amplifier-less long-haul systems. The near-intrinsic purity of SiO_2, enabled by chemical vapor deposition manufacturing methods, coupled with the remarkable strength of silica and scalability of CVD, has led to the present condition where nearly 2 meters of fiber is manufactured every day for each person on Earth. Figure 5.1 shows a phase of the CVD process of manufacturing a glass preform from which an optical fiber will be drawn.

Though the first optical fiber amplifier dates to 1964, the 1990s and early 2000s saw a frenzied focus on optical fiber amplifiers research, initially focused on erbium doped fiber amplifiers (EDFAs), then on praseodymium (Pr) and dysprosium (Dy) doped analogs. The EDFA enabled long haul communications since weakened signals could be all-optically amplified without electro-optical conversion and regeneration. Further, EDFAs operated at 1.55 µm, the wavelength of minimum loss for silica, and are highly efficient. Other wavelengths of interest, such as 1.3 µm where silica glass exhibits zero chromatic dispersion, were expected to afford greater information carrying capacities than operation at 1.55 µm. However, the emissions from Pr and Dy at 1.3 µm are fully quenched given the relatively high vibrational energies in SiO_2 glasses and, so, such amplifiers required low phonon energy glasses, for example the aforementioned fluoride and chalcogenide glass systems. Though much progress was made, including operational networks, in the end, optical fiber systems moved instead to all-silica based components using EDFAs as the amplifiers and dispersion-shifted or compensated fiber designs, originally developed in the late 1970s, to control dispersion and bring together lowest loss and low dispersion at a single wavelength.

Optical fibers, and their ability to confine and guide light, are not only useful for transmission and amplification, but also for nonlinear processes, such as frequency conversion and switching. Whereas transparent fibers usually benefit from low nonlinearity, optical switching and frequency generation require high nonlinearities, where glasses generally gain from components that are weakly bound and heavy relative to, for example, silica. During the 1990s to 2000s, much focus on nonlinear optical fibers centered on chalcogenide and heavy-metal oxide glasses, such as tellurites and germanates [3]. In these glasses, because the nonlinear coefficients can be orders of magnitude larger than those of silica, fiber device lengths are short (cm to meter) and, accordingly, losses are not as critical.

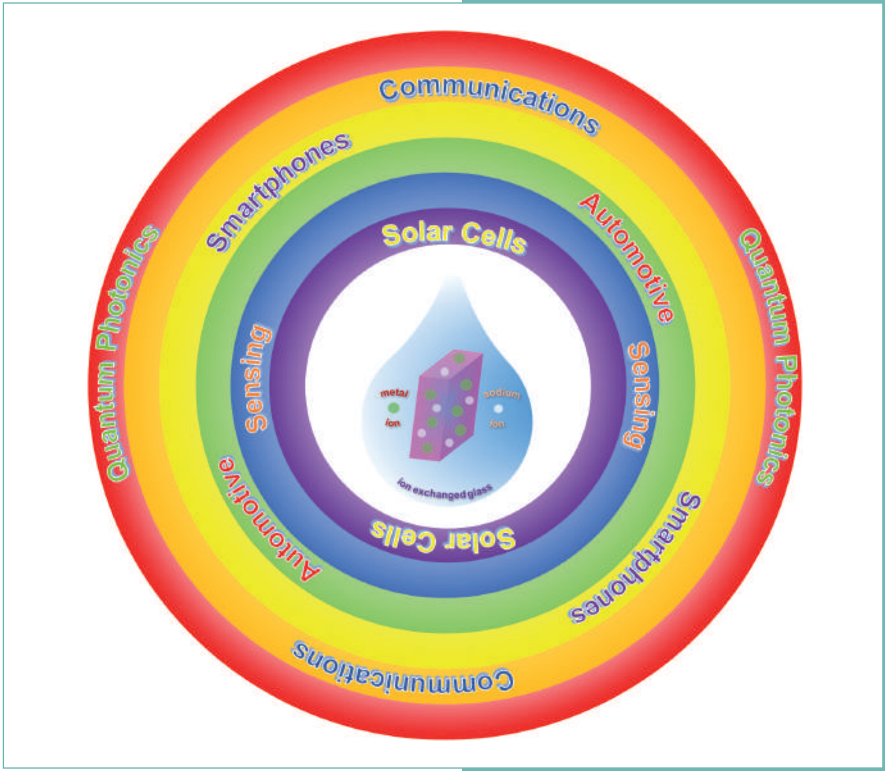


Figure 5.2. A simple sketch of the many application areas of photonic devices implementing the ion-exchange technique.
Source: Courtesy of S. Berneschi.

Following the "dot-com" boom of the late 1990s to early 2000s, optical fibers have enjoyed considerable growth

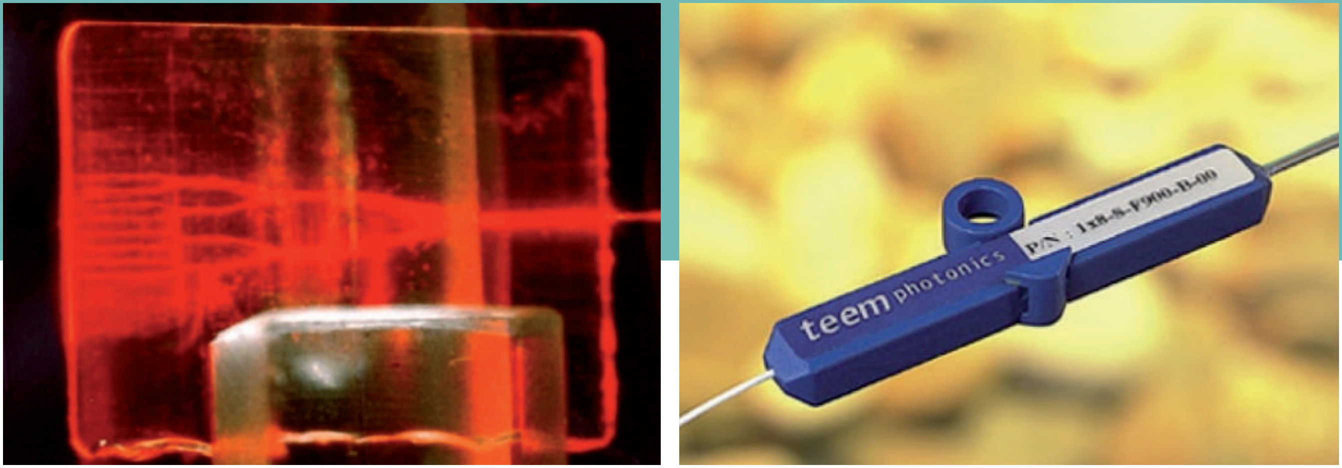


Figure 5.3. An example of a photonic device (1 x 8 power splitter for optical fiber communication systems) made in glass by ion-exchange: (a) laboratory demonstration in 1986; (b) qualified pigtailed and packaged device produced some twenty years later by Teem Photonics.
Source: Reprinted from Ref. [6] under a Common Creative license.

and attention in two main areas. The first is microstructuring including photonic bandgap and microstructured fibers. Though outside the scope of this Chapter, such fibers generally rely on conventional glasses, primarily silica, and performance results typically from periodic structures in the glass(es), or air channels created by stacking rods and tubes together. The second area is in the materials from which fibers are made. Indeed, there has been a renaissance in optical fiber materials, not just in the range of new materials but also in the length scales and interconnectivities ranging from nano-scale engineered structures, including glass-ceramic, phase-separated and nanoparticle infused cores, to multimaterial fibers where glasses, plastics, and metals run the full length [2].

Glass integrated optics

In the mid-1960s it became clear that optical fibers had the capability of winning the competition with metal pipes for long-distance high-capacity communication. Correspondingly, the need emerged for optical connecting elements analogous to existing parallel-plate metal microwave waveguides. Thus, optical thin-film waveguides were designed and fabricated, where light was trapped due to total internal reflections at upper and lower surfaces, i.e., by the same mechanism operating in optical fibers but in a planar geometry rather than a cylindrical one. Shortly thereafter, the new field of integrated optics arose, providing a complete tool for locally manipulating the light coming from a laser source or carried by an optical fiber [4]. Once again, glass immediately emerged as a very convenient material, which had the advantage of full compatibility with optical fibers and provided an easy and low-cost tool to develop technological processes that later could also be transferred to other optical materials.

The fundamental requirement for confining the light is that the guiding layer has a refractive index higher than the surrounding media; this goal, in glass integrated optics, is easily achieved by two dominant approaches, namely a local modification of the bulk glass or the deposition of a thin glass film on a lower-index glass substrate. Indeed, one of the first technologies employed for planar waveguide fabrication, in the early 1970s, was that of ion-exchange in glass, exploiting the same process used for chemical strengthening of glass and already known since the beginning of the 20th century [5]. In fact, the in-diffusion of ions having different atomic size in the pristine glass matrix (e.g., larger potassium ions K^+ from a molten salt KNO_3 substituting smaller sodium ions Na^+ in the glass), while increasing its mechanical strength by preventing or healing over the formation of superficial micro/nano-cracks, at the same time induces an increase of the refractive index at the surface.

Ion exchange was also used in 1968 by Nippon Sheet Glass (NSG) and NEC Corporation for an innovative method to vary the central and peripheral refractive indices of a glass fiber in a parabolic profile, with the aim of reducing the spreading of the envelope of a propagating optical pulse and thus increasing the fiber transmission capacity. Ten years later, these fibers were introduced in the market under the product name of SELFOC®. The major advantage of ion-exchange in integrated optics is the simplicity of the technique, requiring only a furnace, a container of the nitrate salt to be melted, and a proper holder of the sample; its applications in creating optical devices are countless (Figure 5.2).

Regarding material properties, the only strict requirement for the glass is to contain an alkali ion (K^+, Na^+, Li^+ being those most frequently employed). Different glass matrices may be used, depending on the application; soda-lime and borosilicate glasses are among the most common. An example of a glass ion-exchanged integrated optical power splitter device of use in fiber communication systems, is shown in Figure 5.3 [6]; some twenty years were necessary to move from laboratory demonstration (Figure 5.3a: a multi-mode highly scattering sample) to a

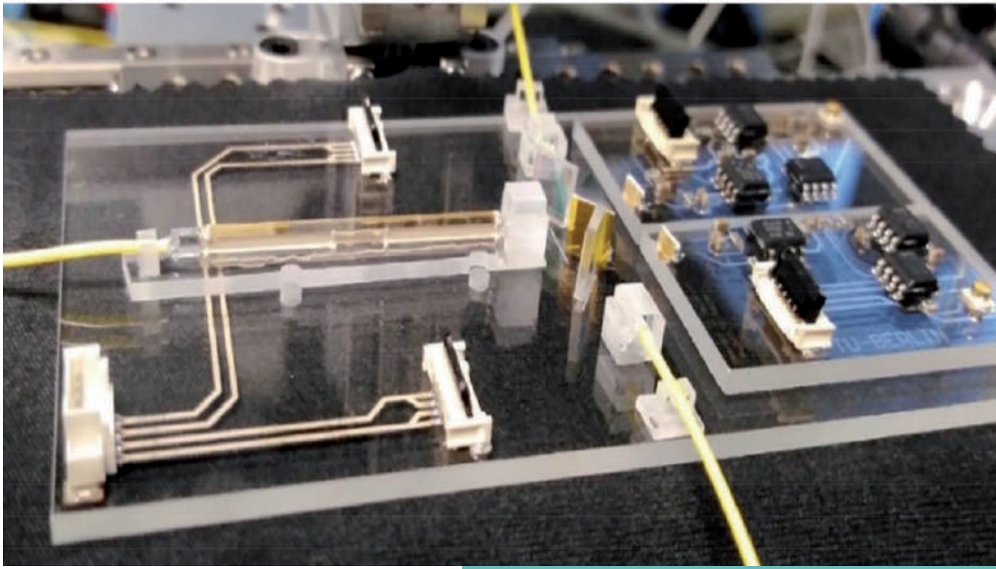


Figure 5.4. Photo of a glass main board: on the left side the light from a fiber-pigtailed external laser is modulated by separately mounted electrodes; at the center, the modulated light is split and coupled into opposite optical fibers, connected to an external sensing device (not visible in the photo); on the right, two separate glass boards detect the light from the sensing unit coming through the same fibers.

Source: Reprinted from Ref. [7] under Creative Commons license.

Telcordia 1209 and 1221 compliant, single-mode, commercially available splitter (Figure 5.3b).

Many other processes have been developed to produce glass optical waveguides and photonic devices, e.g., depositing thin glass films with radio frequency (RF) and magnetron sputtering, chemical vapor deposition (CVD, and in particular plasma-enhanced chemical vapor deposition-PECVD), flame hydrolysis deposition (FHD), spray pyrolysis (SP) deposition, pulsed laser deposition (PLD), and sol-gel coating. Besides ion-exchange, the local modification of refractive index may be achieved by ion implantation, UV irradiation, and femtosecond laser writing; the latter two techniques are also suitable for the direct definition of a channel waveguide circuit.

The continuous advances in microsystems for communication, computing, sensing, and biomedical applications require a higher integration of micro-electronic, optoelectronic and micro-optical components. Even in this area, glass offers unique properties, and advanced hybrid packaging technologies are often based on glass substrates, where photonic integrated circuits (PICs), laser diodes, modulators, isolators, beam splitters, microlenses, and detectors may be interconnected through electrical stripes (i.e., metallized glass) and optical waveguides (possibly with mode field expansion sections). There are, of course, some challenges for the use of glass, such as its poor thermal conductivity and difficulties in free-form cutting and cleaving, but technology keeps advancing to find proper solutions [7]. Several optical, electronic, and mechanical interfaces can be designed in a way that multiple glass boards can be stacked on each other; different modules can be fabricated, ready for assembly on a main glassy board. Figure 5.4 shows as an example a glass main board with size 100 mm x 50 mm, hosting various sub-assemblies: on the left, a system for frequency modulating and splitting the laser light coming from a fiber, and on the right two smaller glass boards detecting the light coming from an external sensing unit through two separate optical fibers [8].

Some innovative guided-wave devices have also been developed thanks to glass properties: an example is constituted by glass microspherical resonators, which find application in narrow-band and add-drop optical filtering, feedback elements for external lasers, multiwavelength and very low-threshold laser sources, nonlinear photonics, and optical sensing. These miniaturized optical resonators are based on dielectric structures having circular symmetry, like cylinders and spheres, which sustain the so-called Whispering Gallery Modes that can be interpreted as circulating electromagnetic waves that are strongly confined within the structure [8]. The peculiar properties of these microresonators are best exploited in the area of sensing: if scattering losses at the surface and absorption of light in the material are very low, the trapped photons are able to circulate for a very long time, providing a very long optical interaction path. Any minimal change at the resonator's boundaries induces a change in the quality factor of the resonator or a shift in the resonance frequency. Thus, detection of small forces, either mechanical or optical (optomechanics), or of micro- or nanoscopic objects (biological ones too, e.g., a bacterium or molecule) is possible with very high sensitivity, even better than the frequently used surface plasmon resonance (SPR) sensors. In the last decades, microspherical devices have fully demonstrated their capability of detecting even single molecules, virions, DNA, antibodies, enzymes, and aptamers. Most of these excellent results have been possible thanks to glass. Pure silica represents the preferred material, due to the very high purity and nanometer-scale surface smoothness available. These two characteristics have made possible the achievement of a top quality factor for the resonator of $Q \approx 8 \times 10^9$, with a corresponding finesse $F \approx 2.2 \times 10^6$. Single spheres with the desired diameter and reproducible high quality are produced very simply by melting the tip of a glass fiber, a very cheap method that allows excellent control of the microsphere diameter.

Another field that has emerged rapidly in recent years to become a hot topic in photonics research is flexible photonics. Its growth has mirrored the rapid development of flexible components and devices (LEDs, OLEDs, displays, wearable sensors) in the area of consumer electronics. At first sight, organic materials would appear the most convenient fabrication platform, due to their mechanical flexibility, low cost and large-scale manufacturing potential; inorganic materials, however, remain the long-term choice for making stable and high-performance photonic devices. Thus, glasses may play an important role even in this area, both as highly transparent, and mechanically, thermally and chemically robust substrates which can also be bent, and as a material platform for optical interconnects and sensor applications. Very thin glasses are now marketed by major glass producers worldwide, with thicknesses in the range 30-200 µm, and are widely used in solar panels and in cellular phones (including foldable phones). There is strong interest in the development of monolithic glass integrated photonic circuits, made in these very thin glasses by direct laser writing, ensuring novel mechanical properties suitable for easier three-dimensional integration of electronic and photonic components. On the other hand, chalcogenide glass waveguides made by thin films thermally evaporated onto polymeric substrates from As_2S_3 binary system or $Ge_{23}Sb_7S_{70}$ ternary alloy have already exhibited excellent characteristics, namely their low deposition temperature, tunability of their refractive index (from 2 to 3.5, depending on composition) and very low propagation loss (less than 1 dB/m) in the band around the 1.5 µm wavelength [9]. This approach appears very promising for new applications such as high-bandwidth-density optical interconnects, conformal wearable sensors and ultrasensitive strain gauges.

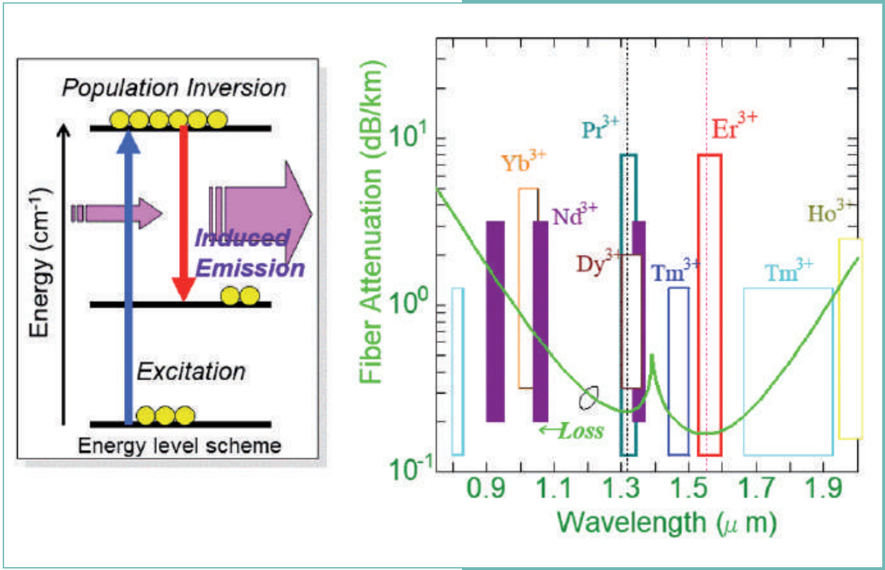


Figure 5.5. Principle of optical amplification with electronic energy levels and some emission bands of active lanthanoid ions in comparison with optical fiber loss spectrum.
Source: S. Tanabe.

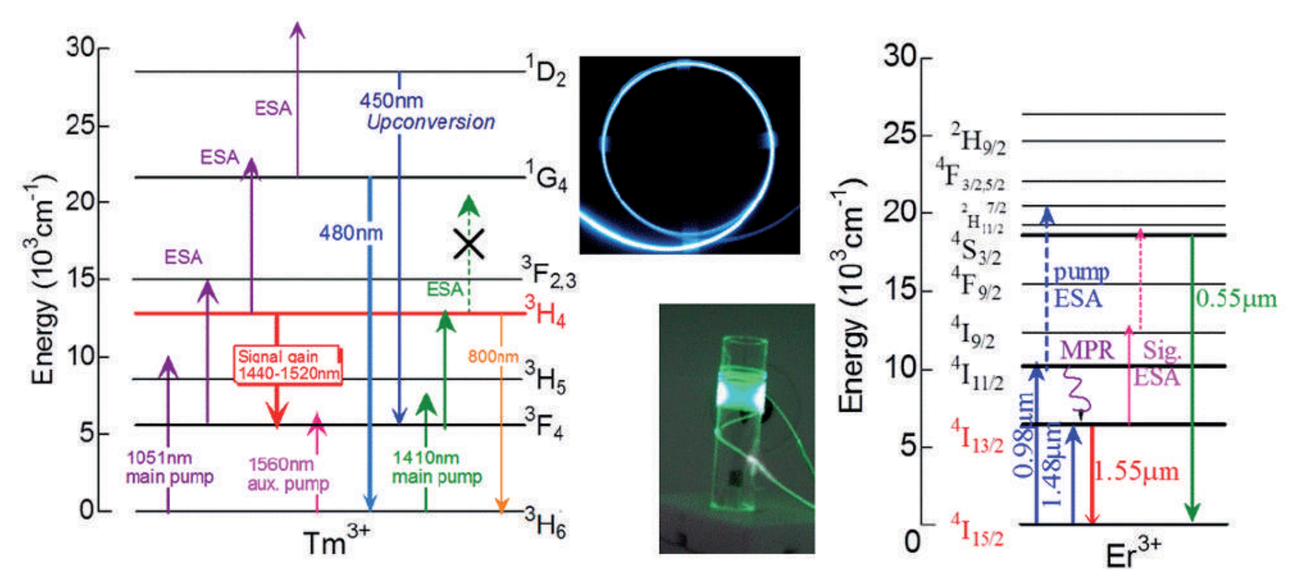


Figure 5.6. Energy level diagrams and important electronic transitions of Tm^{3+} and Er^{3+} ions for optical amplifications and infrared-to-visible upconversion by excited-state absorption (ESA) mechanisms. Blue and green luminescent fibers in two photos are Tm-doped and Er-doped ones excited by the corresponding NIR LD for telecom amplification.

Source: S. Tanabe.

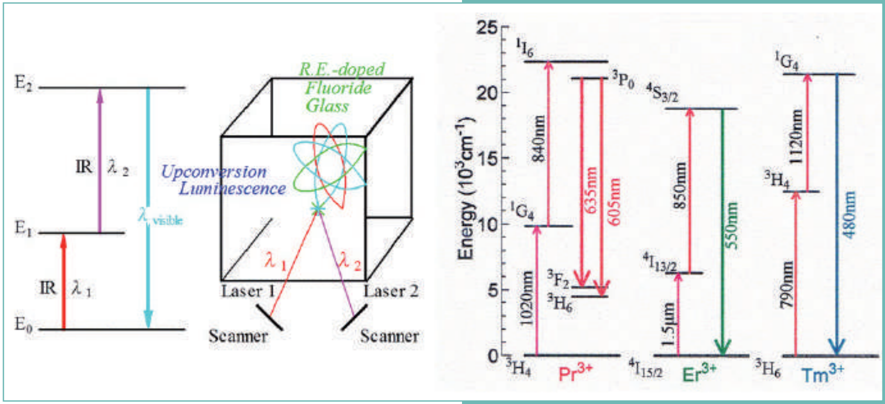
Active glasses and 3D displays

The first glass laser, using a neodymium-doped silicate glass, was developed in 1961 [10], just after the invention of the first laser (ruby) [11] for humankind in 1960. Subsequently, several important developments in glass-based active devices followed, before the global installation of optical fiber telecommunication [12, 13]. Most active devices utilize the luminescence and/or its stimulated emission of lanthanoids' 4f electronic transitions. Figure 5.5 shows the principle of optical amplification with electronic energy levels and representative emission bands of active lanthanoid ions in comparison with the (silica) optical fiber loss spectrum, which has the minimum loss at 1.55 μm.

As noted in Section 2, relating to telecommunication systems, the invention of the EDFA [14] can be likened to that of the transistors in electronics in terms of its technological impact. The technology to amplify the light signal directly without the conversion of light/electricity/light is achieved by stimulated emission of a 4f optical transition in rare-earth-doped silica glass fibers and realizes ideal amplification with high gain and low noise. The technological development of optical telecommunication is based on the growth of technologies of fiber fabrication and those of laser diodes (LD). In fact, the invention of efficient III-V LDs and their fiber coupling has also enabled efficient pumping of Er^{3+} with its three-level system. In addition, the history of the technological

Figure 5.7. Principle of 3D color display utilizing the dual-NIR-pumped visible upconversion and the energy levels of RGB luminescent ions; Pr^{3+}, Er^{3+}, Tm^{3+} [23]. Some intermediate excited levels of lesser importance are omitted for simplification.

Source: S. Tanabe.



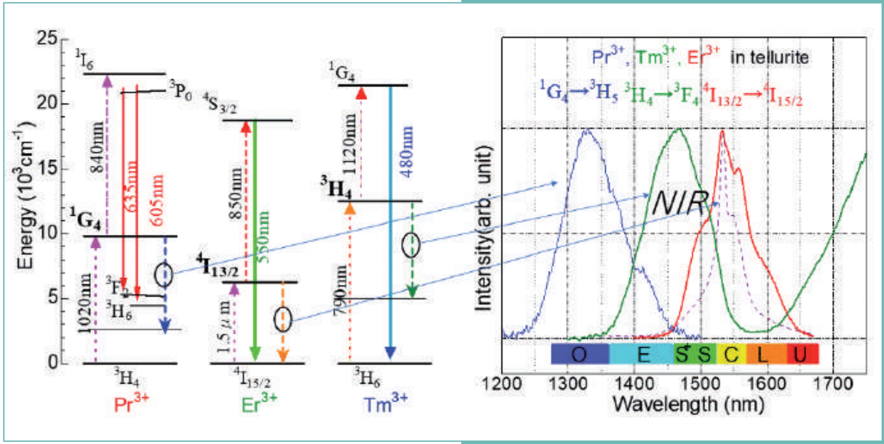


Figure 5.8. Left: Energy levels of RGB luminescent center ions, Pr^{3+}, Er^{3+}, Tm^{3+}, showing NIR amplification transitions at the O-, S-, and C+L-bands of optical fiber telecommunication. Right: NIR PL spectra of these same ions [25].

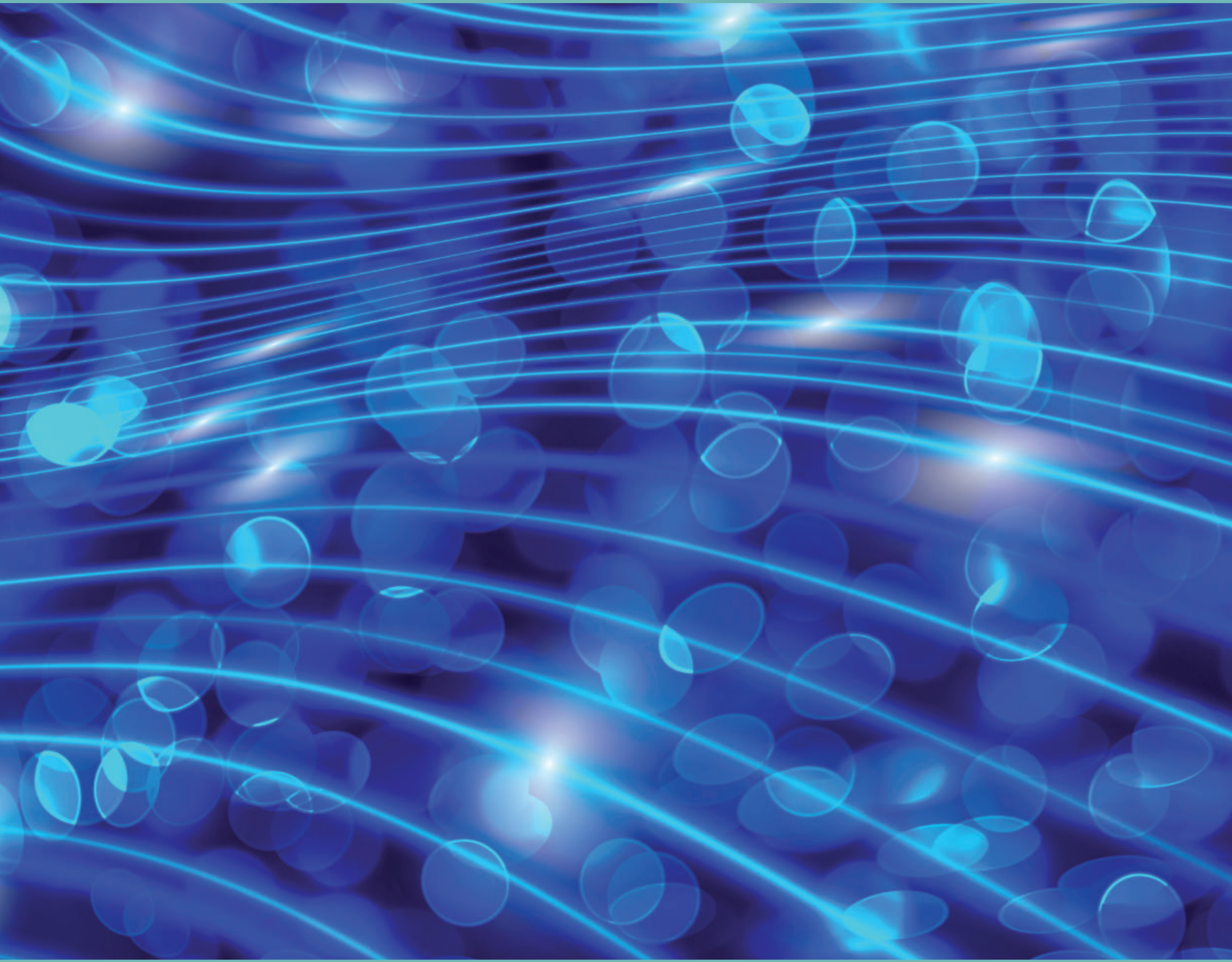
Source: S. Tanabe.

transition from passive fibers to active fibers also demonstrates the interesting relationship between active ions and the host glasses.

Although fiber amplifiers are already playing crucial roles in the optical networks both at the 1.55 µm and 1.3 µm bands, further requirements exist to fully utilize the windows of optical fibers with superior performance. The requirements are a wide and flat gain spectrum around 1.53~1.65 µm (C+L band) in a novel EDFA and around 1.4~1.51 µm (S-band) in Tm^{3+} (TDFA) for wavelength division multiplexing (WDM) systems [15], and greater gain per pump-power at 1.31 µm in Pr^{3+} [16].

In the research history of rare-earth doped glasses, also noteworthy are various efforts to develop blue and green lasers by up-conversion luminescence of Pr^{3+}, Ho^{3+}, Er^{3+} and Tm^{3+} ions, mainly in fluoride glass hosts, during the late 1980s and early 1990s, before the invention of blue LED or LD based on GaN [17,18]. Some of these transitions are shown in Figure 5.6. High-power LDs in the NIR developed for fiber telecommunication in the late 1980s have stimulated research because of the possibility of a visible laser by pumping with the LDs.

Fluoride glasses developed so far [19] are an ideal host to give the lanthanide dopant ions a low-phonon-energy environment and thus long excited state lifetimes, enabling efficient multi-step pumping and high luminescence



quantum efficiency for the excited levels even with a narrow energy gap to the next lower level [20]. According to studies and theories [21,22], the lower the phonon energy of the host is, the smaller are nonradiative losses due to multiphonon relaxation yielding longer fluorescence lifetimes from the excited states. This situation becomes critical when the energy level separation between associated electronic levels is not large, which is true for most excited states of Pr^{3+}, Ho^{3+}, Er^{3+} and Tm^{3+} ions [23]. A long fluorescence lifetime gives a higher probability of the second- (sometimes also the third- and fourth-) step excitation to intermediate excited levels and then, a higher radiative quantum efficiency to the luminescent terminal state.

Intrinsically, fluoride hosts have a wide optical transmission window, because of their short ultraviolet (UV) absorption edge (band gap) and long infrared absorption (multi-phonon) edge. The UV edge of fluorides is short enough to be a UV laser host for ions like Tm^{3+}, and the infrared (IR) edge is long enough for IR pumping or to be an IR light source.

One interesting application of up-conversion is a 3D display by dual wavelength pumping schemes for three active centers, which was proposed in 1996 by E. Downing [24]; the scheme of operation and the relevant energy levels are illustrated in Figure 5.7.

Fluoride glasses remain one of the best possible hosts due to their stability and efficiency. It is interesting to note that three active lanthanide ions for red/green/blue (RGB) colors (Pr, Er, Tm) are also active centers for the telecom amplifiers at O-, C- and S-bands, respectively, in the near-IR (NIR). Figure 5.8 shows the photoluminescence spectra of the three elements in relation to the NIR telecom bands [24].

Summary

The future of glass is even brighter than the past, given the centrality of data to virtually all sectors of modern life. Infrastructure modernization, autonomous mobility, 5G and quantum communications will all rely on ultra-high capacity and information-secure glasses, whether in bulk, planar or fiber form. Areas deserving special attention relating to the future of optical fiber glasses include: high energy fiber lasers where performance is presently limited by already weak nonlinearities in the glass; thermal management using fibers such as laser cooling and radiation-balanced lasers and amplifiers; and long wavelength (>2.5 μm) infrared fibers and fiber lasers for chemical and biological sensing and power-delivery. In parallel, one can expect further advances related to glass integrated optics, including planar active devices (lasers and amplifiers) and photonic guided-wave components for frequency modulation and multiplexing (mux-demux) and optical switching, based on nonlinear optical properties of high-index and nanostructured glasses. Optical interconnectsfor high integration of optoelectronic components will also exploit the properties of various glasses; in this regard, a wider use of ultrathin glasses (now mainly employed for the cover of cell phones and displays) is envisaged, because of the addition of mechanical flexibility to the pristine optical properties of glass.

In summary, we have entered an age that is dominated by light and glass and there is a growing appreciation that glass science and optical waveguide engineering are the best approaches to address current limitations in a wide variety of glass-based photonic systems.

References

[1] Ballato, J. & Dragic, P. D. (2021): "Glass: The carrier of light (Part II). A brief look into the future of optical fiber", *International Journal of Applied Glass Science*, 12: 3-24.

[2] Ballato, J. & Dragic, P. D. (2016): "Glass: The carrier of light. A brief history of optical fiber", *International Journal of Applied Glass Science*, 7: 413-422.

[3] Ballato, J. & Dragic, P. D. (2016): "Glass: The carrier of light. A brief history of optical fiber", *International Journal of Applied Glass Science*, 7: 413-422.

[4] Tao, G. *et al.* (2015): "Infrared fibers", *Advances in Optics and Photonics*, 7: 379-458.

[5] Righini, G. C. & Pelli, S. (2020): "1969-2019: 50 years of integrated optics", *Integrated Optics*, 1: 1-38.

[6] Berneschi, S.; Righini, G. C. & Pelli, S. (2021): "Towards a Glass New World: The Role of Ion-Exchange in Modern Technology", *Applied Sciences*, 11: 4610.

[7] Broquin, J. E. & Honkanen, S. (2021): "Integrated Photonics on Glass: A Review of the Ion-Exchange Technology Achievements", *Applied Sciences*, 11: 4472.

[8] Schröder, H. *et al.* (2021): "Hybrid photonic system integration using thin glass platform technology", *Journal of Optical Microsystems*, 1: 033501.

[9] Righini, G. C. *et al.* (2011): "Whispering gallery mode microresonators: fundamentals and applications", *Rivista del Nuovo Cimento*, 34: 435-488.

[10] Li, L. *et al.* (2014): "Integrated flexible chalcogenide glass photonic devices", *Nature Photonics*, 8: 643-649.

[11] Snitzer, E. (1961): "Optical maser action of Nd^{3+} in a barium crown glass", *Physical Review Letters*, 7: 444-446.

[12] Maiman, T. H. (1960): "Stimulated Optical radiation in Ruby", *Nature*, 187: 493-494.

[13] Koestner, C. J. & Snitzer, E. (1964): "Amplification in a fiber laser", *Applied Optics*, 3: 1182-1186.

[14] Snitzer, E. & Woodcock, R. (1965): "Yb-Er glass laser", *Applied Physics Letters*, 6: 45-46.

[15] Mears, R. J. *et al.* (1987): "Low-noise erbium-doped fibre amplifier operating at 1.54 µm", *Electronics Letters*, 23: 1026-1028.

[16] Komukai, T. *et al.* (1995): "Up-conversion pumped thulium-doped fluoride fiber amplifier and laser operation at 1.47 µm", *IEEE Journal of Quantum Electronics*, 31: 1880-1889.

[17] Ohishi, Y. *et al.* (1991): "A high gain, high output saturation power Pr^{3+} -doped fluoride fiber amplifier operating at 1.3 µm", *IEEE Photonics Technology Letters*, 3: 715-717.

[18] Akasaki, I. *et al.* (1995): "Stimulated Emission by Current Injection from an AlGaN/GaN/GaInN Quantum Well Device", *Japanese Journal of Applied Physics*, 34: L1517-L1519.

[19] Nakamura, S. *et al.* (1996): "Room-temperature continuous-wave operation of InGaN multi-quantum-well structure laser diodes", *Applied Physics Letters*, 69: 4056-4058.

[20] Lucas, J. (1985): “Rare earths in fluoride glasses”, *Journal of the Less Common Metals*, 112: 27-40.

[21] Tanabe, S. (1999): “Optical transitions of rare-earth ions for amplifiers: How the local structure works in glass”, *Journal of Non-Crystalline Solids*, 259: 1-9.

[22] Layne, C. B.; Lowdermilk, W. H. & Weber, M. J. (1977): “Multiphonon relaxation of rare-earth ions in oxide glasses”, *Physical Review B*, 16: 10-20.

[23] Tanabe, S. (2002): “Rare-earth-doped glasses for fiber amplifiers in broadband telecommunication”, *Comptes Rendus Chimie*, 5: 815-824.

[24] Downing, E. *et al.* (1996): “A three-color, solid-state, three-dimensional display”, *Science*, 275: 1185-1189.

[25] Tanabe, S. (2015): “Glass and Rare-Earth Elements: A Personal Perspective”, *The International Journal of Applied Glass Science*, 6: 305-328.

Sol Camacho

6. Reflections on Reflection: Glass in Architecture

To speak about glass in architecture is to speak about the history of architecture of the past two hundred years, and that is a daunting task for an architect who has merely been studying this for a few years. I arrived at this subject almost randomly. My research on the subject grew as a derivative of my interest in the life and work of the Italo-Brazilian architect Lina Bo Bardi (1914-1992), who pioneered in the use of the material with two of her most iconic buildings, her own house in Morumbi —today known as the *Casa de Vidro* (1951) (Figure 6.1) and the Museu de Arte de São Paulo Assis Chateaubriand (1968), also known as MASP (Figure 6.2).

I arrived to live in São Paulo in 2011 and these two canonic examples of Brazilian Architecture were my introduction to the city; by studying about them I was able to connect with people and the history of the fascinating South American metropolis. These buildings condense the life and work of Lina —as she is locally known— and Pietro Maria Bardi (1900-1999), her husband, journalist and art critic founder of the MASP.

The couple arrived in 1946 from a torn-down Italy to a promising Rio de Janeiro and soon met Assis Chateaubriand (1892-1968), a media mogul[1] who commissioned Bardi to found and direct an art museum in São Paulo in 1947, first inside the office building of *Diários Associados* on *Rua 7 de Abril*. With his critical eye and knowledge of European Art, Bardi built during the years one of the largest and

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[1] Assis Chateaubriand owned and directed the media conglomerate *Diários Associados* and was a pioneer entrepreneur with the TV Tupi, the first TV in Brazil.

Figure 6.1. Lina Bo Bardi's *Casa de Vidro.*
Source: Nelson Kon.

most important art collections in Latin America with a pioneering educational program that weaved the arts with other disciplines in the style of the Bauhaus. His knowledge and understanding of architecture had been acquired in his years as journalist in Italy, Bardi was an active member of modernist circles and exchanged letters to Le Corbusier, Walter Gropius and Richard Neutra.

Italy at the time was under the fascist regime that came into power in 1922 and modernism was in a delicate situation, if it enjoyed state sponsorship, it was also being persecuted by opposing factions. As there was no official-promoted art, exhibitions and building commissions were disputed to gain favor with the state. While Giuseppe Terragni was working in his *Casa del fascio de Como* that became one of the icons of Italian Modernism and of glass architecture, Marcelo Piacentini consolidated through politics his position as leading architect with neoclassicism as the core architecture movement.

The dispute over modernism and neoclassicism would extend even further than Italy. Brazil had open relations with Fascist Italy due the populist dictatorship of Getúlio Vargas. If Bardi went to Brazil before the war to promote modernism to the Americas, Piacentini came to São Paulo on a diplomatic mission invited by the Italo-Brazilian industrialist Matarazzo family[2]. Later political changes, such as a surprising pro-USA stance of Vargas in the event of the Second World War, would lead the Matarazzo to a pro-modernist stance with the sponsorship of the Museum of Modern Art of São Paulo in 1948 at the same building of MASP at *Rua 7 de Abril*, and later to its location at Ibirapuera Park designed by Oscar Niemeyer.

During the years 1938-1943 [1], in what can be interpreted as one of Bardi's last contributions to Italian critics before immigrating to Brazil, he worked in the magazine *Il Vetro* (Figure 6.3); but, he was forbidden by the regime to sign his text and his name wasn't listed on the credits. *Il Vetro* was, as the italian name implies, a magazine around themes and uses of glass. In his contribution, Bardi wrote not only about technical uses of glass, but also wrote about glass architecture. Italian fascism had tried to incorporate in its rhetoric glass as a metaphor for the State, a metaphor which Terragni heavily leaned on as the new foundation of Italian architecture,

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[2] Piacentini designed for the Matarazzo family their corporate headquarters in Vale do Anhangabaú and their mansion at Avenida Paulista. The corporate headquarters was later acquired by the state and since 2004 is São Paulo's town hall. The mansion at Avenida Paulista was demolished to give place to a shopping mall.

Figure 6.2. Lina Bo Bardi's MASP.
Source: Nelson Kon.

but ultimately lost to Piacentini's neoclassicism.

However, *Il Vetro* was one later addition to the ample debate of glass architecture as modern architecture, if not one of the last magazines to debate glass architecture before and during the Second World War. There is no easy answer for when the concept of glass architecture begins, contemporary critics tend to inscribe the beginning of glass architecture to the first decades of the 20th century; but Walter Benjamin in the 1920s studied a possible transition of glass as material to glass as architecture in the 19th century. On the words of his notes of the incomplete project on the arcades of Paris:

> *Glass before its time, premature iron. In the arcades, both the most brittle and the strongest materials suffered breakage; in a certain sense, they were deflowered. Around the middle of the past century, it was not yet known how to build with glass and iron* [2].

Nevertheless, Glass has fascinated men over centuries way before any modern possibilities. Europe was dotted with colorful cathedrals, mirrored hallways and fogged greenhouses, and glass was used in artifacts and buildings all around the world without direct correlation to European arts and crafts.


Av. Paulista

Figure 6.3. *Il Vetro* magazine covers.
Source: Instituto Bardi.

This fascination was always hindered by a limited supply and production of glass, a limitation that reduced the material to a luxury status. The Industrial Revolution unleashed new ways to mass produce glass in panes or common artifacts. Ample supplies and cheap production turned glass into a more affordable material to build even the simplest of structures (Figure 6.4).

What Benjamin's research argues is a change in the cultural and popular consensus around the use of glass with the construction and inauguration of Paxton's Crystal Palace. While the arcades of Paris were a modern life predecessor of the Crystal Palace, it was Paxton's work to set the material of a modern architecture in Europe, correlated to the industrial progress of its time. Benjamin also argues that the 19th century glass architecture was correlated to velocity and temporary structures [3], since it was used mostly on railroad stations and exhibitions palaces[3], while the 20th century glass architecture was seen as stable and solid due a change of social perception of time.

As new materials and structural principles were discovered and pioneered in the 19th century such as the glass curtain wall and reinforced concrete, mostly developed due the zealous work of engineers and pioneer architects, a search for a transcendental meaning for glass architecture pertains to art and architecture debates of the 20th century.

Literature led the way before architecture, German author Paul Scheerbart was one of the first to attribute to glass a new spiritual sense and utopic possibility both in a manifesto and novels. Also the French authors André Breton and Louis Aragon would explore the glass at the arcades in surrealist novels. Scheerbart would be of great impact to Bruno Taut's early works and publications on modern architecture, Taut's book *Alpine Architecture* [4] and the construction of the Glass Pavilion for the 1914 Werkbund (Figure 6.5) were among the first works to present colorful glass as a medium of modern spirituality, architecture and industry. On the other hand, Breton and Aragon would be the bases of Benjamin's critics of bourgeois privacity and defense for a transparent glass architecture of the proletariat, one that could not bear traces of ownership.


Figure 6.4. Bureau of Standards making extensive tests of glass building blocks (Washington DC).
Source: Library of Congress.

Another major debate was in the meaning of the American skyscraper and how to translate the typology to Europe. While the USSR saw the skyscraper as a symbol of American capitalism, even with important unrealized projects such as El Lissitzky's Cloud Iron, the German architects were among the first to correlate the stained-glass cathedral to the glass skyscraper. Be it on Bruno Taut's *Stadkroner* [5], or on Walter Gropius' *Bauhaus Manifesto* cover illustrated with Lyonel Feninger's

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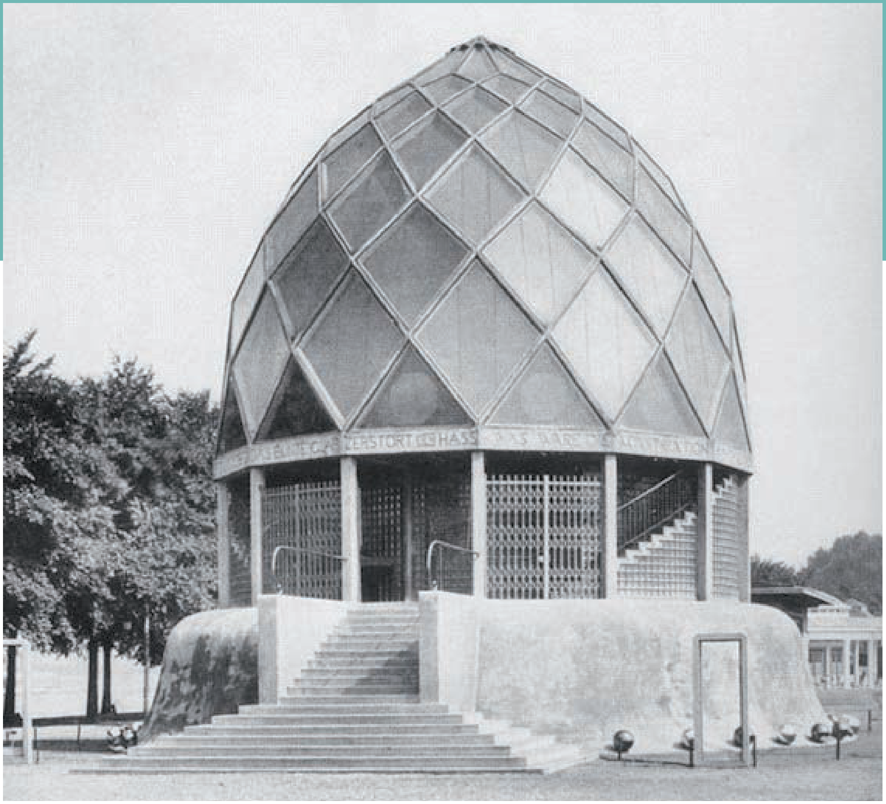
[3] Other famous palaces of glass and iron besides the English Crystal Palace were the French Galerie des Machines and Grand Palais.

Cathedral, the skyscraper was understood as a modern spiritual equivalent to the historical cathedral [6].

In the Americas, Frank Lloyd Wright explored the possibilities of both stained-glass and transparent glass panes, as a medium that could overcome classicism and achieve a true representation of the modern ways of the United States [7]. The Larkin Building, famous for its glass skylights over the atrium, was deeply connected to a religious sense of work with its salomonic floor plan, carved inscription and a pipe organ. The later Johnson Wax Building had a more industrial and practical application of Pyrex glass, still the architect had planned the installation of a pipe organ to the main office. On the other hand, Albert Khan was applying glass skylights and glass curtain walls to all his designs of Ford Plants to improve working conditions and reduce operation costs. 20th century industrial plants were almost a new form of architecture in themselves, one that demanded new technologies and material applications. If there was the skyscraper, there were also the industrial plant inserted on the debate of the modern cathedral, it is not casually that Peter Brehens' AEG Factory was nicknamed "cathedral of work".

Figure 6.5. Bruno Taut's Glass Pavilion for the 1914 Werkbund.
Source: Wikimedia Commons.



Still, it was transparent glass over its colorful counterpart that became the general norm to modern architecture. As Scheerbart and Taut were both debating over the spiritual sense of modernity, Le Corbusier and Walter Gropius were focusing on the technical applications and social benefits. Glass was not only the material to build a new transparent society after the Great War, as Beatriz Colomina's *X-Ray Architecture* [8] attest, glass was a material correlated to new sanitary measures against tuberculosis and other diseases. Sanatoriums were also a modern form where glass flourished, Alvar Aalto's Paimio Sanatorium being one of the exemplary cases of the relation of modern architecture, health and glass;

Figure 6.6. Mies van der Rohe's Tugendhat Villa.
Source: Wikimedia Commons.

however the same could be applied in a private dimension to Neutra's Lovell House and Mies van der Rohe's Tugendhat Villa (Figure 6.6).

What becomes clear from the 20th century debate is that there isn't a single common root or a primordial form of glass architecture. Even Paxton's Crystal Palace, being the most prominent candidate to the position, is a parallel event to the arcades of Paris, which cannot be considered as isolated from the city. However, it is possible to search for traces and correlations between different works in their historical context. As such, the Crystal Palace was a development of the techniques applied on the construction of English greenhouses, and the arcade of Paris were consequential to the urbanization of Paris from the late 18th century. While technology can partially explain the development of glass, it lacks means to explain the social reality behind glass architecture. Therefore, a typological study opens the possibility to create a non-exclusionary presentation of glass architecture, one that is capable of a critical reading of most works along a chronological distribution.

Figure 6.7. Glass house's bookshelves designed by Lina Bo Bardi.
Source: Instituto Bardi.

Typology dictates both about constructed space and human interaction with space, if typology can be reduced to a list or diagrammatic distribution of spaces, it is meaningful only with human action on the space. Since glass architecture doesn't have a single theoretical root, it also doesn't have a single typological origin, opening the possibility to parallel typological developments. While it is straightforward with the arcades of Paris —because they can be traced as an origin point for the typological sequence of commercial galleries, department stores and even shopping centers—, the Crystal Palace, being the first exhibition palace, is typologically in between two distinct functions and spatial dimensions. As it's possible to trace back the structure of glass and iron to the greenhouse and the later to stone and glass orangeries of royal palaces, from the Crystal Palace onwards there is a development of typologies focused on human interchange such as other exhibition palaces, modern expositive pavilions and convention centers.

Modern Pavilions are another key typology to understand the development of glass architecture, many were constructed both as synthesis of an ideal and a proof of concept for architecture. All of them were built as temporary structures where architects experimented with new construction techniques and materials. Bruno Taut's Glass Pavilion, Le Corbusier's L'Esprit Nouveau Pavilion and Mies van der Rohe's Barcelona Pavilion are some of the most iconic examples that explored glass in relation to architecture; but specially with Le Corbusier and Mies van der Rohe it is possible to note a development of a language of glass architecture expressed in a synthetic manner on their pavilions. The same can be said of Oscar Niemeyer and Lucio Costa's New York Pavilion for the 1939 World's Fair in the context of Brazilian

Modernism while the first major work, the Ministry of Education and Public Health, was still under construction.

In the works of Mies van der Rohe, with both the Tugendhat Villa and Barcelona Pavilion, it is possible to note a correlation of modern pavilion and glass house. This correlation is also present in Le Corbusier and Niemeyer, among other early 20th century architects. As glass architecture consolidated itself as a modern language, the mid-century architects constructed a considerable amount of their glass houses in reference to early pavilions and glass houses. Philip Johnson and Lina Bo Bardi are prime examples of mid-century glass house architects.

Still, this transition from the pavilion typology to the glass house typology is an ample one, the glass house or modern house are both a convergence of the experiences of the modern pavilion with the traditional bourgeois house due the clients' social status. Therefore, the glass house possesses a social dimension in relation to its owners and easily typological study becomes a biography of the relation of house and owners. While Dr. Edith Farnsworth complex relation with Mies' Farnsworth House is the most commonly known and well-documented example, here we should turn our attention back to Lina Bo Bardi and Pietro Maria Bardi with their *Casa de Vidro* (Figure 6.7):

> *The Bardi's history is interchangeable with the Museum of Art of São Paulo, with Pietro being the first director of the institution and Lina being the chief architect of the building at Avenida Paulista. Before the present day museum, Pietro and Lina organized the first gallery of MASP at* Rua 7 de Abril*, while not in a proper sense a "pavilion" or glass architecture for the matter, it was an important experience on expography and museography, and Lina would adopt some solutions both in her glass house's bookshelves and in the new museum main exhibition hall*[4].

The *Casa de Vidro* was conceived as an extension of the cultural program of MASP, a centerpiece on a network of guest houses to be constructed for artists and curators that Bardi exchanged letters and critical essays. As such, the main hall glass of the *Casa de Vidro* with its dining room, living room and office was designed as a room for this network of houses, facing with three complete glass facades the landscape of an unoccupied suburb of Morumbi in São Paulo. Lina's glass house also kept a courtyard disposition of private spaces with a clear division between the owner's rooms and service spaces, striking an interesting equilibrium of modern lifestyle and traditional praxis.

Even when the network of guest houses was abandoned as a project, the main hall kept its concept as public space inside the private sphere. Pietro Maria's business as both director of MASP and art dealer made the place a diversified art gallery, and Lina's collections of Brazilian regional crafts juxtaposed high arts with local craftsmanship. Trees and other plants created a green landscape around the house as Morumbi was integrated in the urban landscape as an elite neighborhood. Glass transparency that was once defined by the hills, horizon and sky became a close shadowplay of trees and nature (Figure 6.8).

The MASP at the bustling Avenida Paulista also establishes a relation of art and landscape through glass in the main exhibition hall: as the southwest facade opens a view to the top of the trees at Trianon Park, the northeast facades creates a vista to the axis of Avenida 9 de Julho and the historic city center. While most of the time the facades are not completely open to the landscape to protect the art from adverse effects of sunlight, the "glass easels" (Figure 6.9) supporting the paintings create a "collage-effect" inside the main exhibition hall, with the visual juxtaposition of styles and ages.

Glass architecture came to build not only a new perception of space and art, but a new material reality for cities across the globe. From idyllic houses

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[4] The second concrete-enclosed gallery of MASP at Avenida Paulista resembles to a certain degree the space *Rua 7 de Abril* gallery with a museographic approach varying with curatorship.

Figure 6.8. Reflections on the glass of the facade of the Glass House.

Source: Yghor Boy/Instituto Bardi.

Figure 6.9. Lina and the "glass easel". MASP main exhibition hall under construction.
Source: Lew Parrella/Instituto Bardi.

to monolithic towers, glass became a common shared experience of modern and contemporary lifestyle; but it also became part of a problem as much as a technical solution. As one of its advantages is transparency and heating through solar radiation, its widespread use disregarding local climate leads to an increasing consumption of electricity and resources through air-conditioning machines, and both transparency and reflexivity contributed to the formation of urban heat islands and overall increase of a city's temperature. For that, the glass and glazing industry offers many technical solutions, and advances are now moving towards the construction of buildings that are energy neutral or even can contribute to the energy grid.

So, if Walter Benjamin argues that in the first half of the 19th century it was still known how to build with glass in the heights of the Industrial Revolution, today one could say that in the first half of the 21th century we are undoubtedly expanding the knowledge on how to build an environment-aware glass in the age of climate changes. Glass architecture goes beyond the debate of ethics and aesthetics, it is the practical reality of cities and can be an integral part of an environmental solution to contemporary challenges. The International Year of Glass presents this unique opportunity to recapitulate the past two hundred years of glass architecture and think of a new future for the city of glass, to overcome its challenges and create new social perspectives. It allows architecture to go beyond the traditional constraints of the disciplinary field and be part of a coordinated debate about glass. To a certain degree, the International Year of Glass reinserts the debate of glass architecture in the 2020s and opens up the possibilities to review what was discussed only as utopies in the 1920s, perhaps even speculate what new typologies could develop from contemporary glass and new technological means of production.

If there is urgency in solving pressing matters today, glass architecture should also concern with what comes of tomorrow as once it was seen as a clear future in itself.

Acknowledgements

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References

[1] Tentori (2000): 150-152. Esmeraldo, E. G. (2020): *AMER. A primeira América de Bardi: diário de bordo de P. M. Bardi (1933-1934)*, Unicamp.

[2] Benjamin, W. & Tiedemann, R. (1999): *The arcades project*, Cambridge, Belknap Press: 150.

[3] Benjamin, W. & Tiedemann, R. (1999): *The arcades project*, Cambridge, Belknap Press: 154.

[4] Schirren, M. (2004): *Bruno Taut, Alpine Architektur. Eine Utopie, A Utopia*, Munchen, Prestel: 36.

[5] Taut, B. (2015): *The City Crown*, Surrey, Ashgate Publishing.

[6] Tafuri, M. (1987): *The Sphere and the Labyrinth: Avant-Gardes and Architecture from Piranesi to the 1970s*, Cambridge, MIT Press: 125.

[7] Wright, F. (2008): *Modern Architecture: being the Kahn lectures for 1930*, Princeton, Princeton University Press: 38.

[8] Colomina, B. (2019): *X-Ray architecture*, Zürich, Lars Müller Publishers.

Further reading

Benjamin, W. (1986): “Surrealism: The Last Snapshot of European Intelligentsia”, in S. E. Bronner & D. M. Kellner (editors), *Critical Theory and Society*, Routledge.

— (1999): “Experience and Poverty” in *Walter Benjamin: Selected Writings Vol. 2*, Harvard University Press.

Benjamin, W. & Tiedemann, R. (1999): *The arcades project*, Cambridge, Belknap Press.

Colomina, B. (2019): *X-Ray architecture*, Zürich, Lars Müller Publishers.

Esmeraldo, E. G. (2020): *AMER. A primeira América de Bardi: diário de bordo de P. M. Bardi (1933-1934)*, Unicamp.

Gropius, W. (1965): *The New Architecture and the Bauhaus*, Cambridge, MIT Press.

Le Corbusier (1964): *When Cathedrals were White*, McGraw-Hill Paperback.

Le Corbusier; Sirton, P. & Berton, T. (2012): “Glass the Fundamental Material of Modern Architecture”, *West 86th: A Journal of Decorative Arts, Design History, and Material Culture*, 19 (2).

SCHIRREN, M. (2004): *Bruno Taut, Alpine Architektur. Eine Utopie, A Utopia*, Munchen, Prestel.

TAFURI, M. (1987): *The Sphere and the Labyrinth: Avant-Gardes and Architecture from Piranesi to the 1970s*, Cambridge, MIT Press.

TAUT, B. (2015): *The City Crown*, Surrey, Ashgate Publishing.

WRIGHT, F. (2008): *Modern Architecture: being the Kahn lectures for 1930*, Princeton, Princeton University Press.

ERIK MUIJSENBERG

7. Sustainable Glass Production with Carbon Reduction

Sustainable glass recycling (UN Goal 11)

Glass plays an important role in our society. Its usage in housing, transportation, communication, food storage, etc. is crucial to enjoying a high quality of life. To produce glass, we need raw materials and energy. We can reduce the need for materials by recycling more. Indeed a significant advantage of glass is that it can be endlessly recycled without loss in quality or purity although glass waste needs to be purified, cleaned, and color separated before use [1] [2].

Using more cullet for melting means not only considerable savings in raw materials costs and energy usage, but CO_2 emissions are also lower. Clean cullet needs to be reheated and homogenized; but melting reaction energy is not required and every 10% cullet addition reduces the energy consumption of glass melting by 2-3%. To melt soda lime glass from raw materials requires a theoretical energy of about 2.6 MJ/kg. As pure cullet, this is reduced to 1.9 MJ/kg. More importantly, re-melting cullet avoids CO_2 emissions from soda ash (Na_2CO_3) and lime ($CaCO_3$) in the batch. Every metric ton of waste glass recycling saves about 315 kg of CO_2 that would be released manufacturing a new glass product [3]. However, the most common, efficient, end-fired container glass furnaces, melting with an average of 50% cullet, consume about 3.5 MJ/kg, due to additional heat losses through the furnace structure.

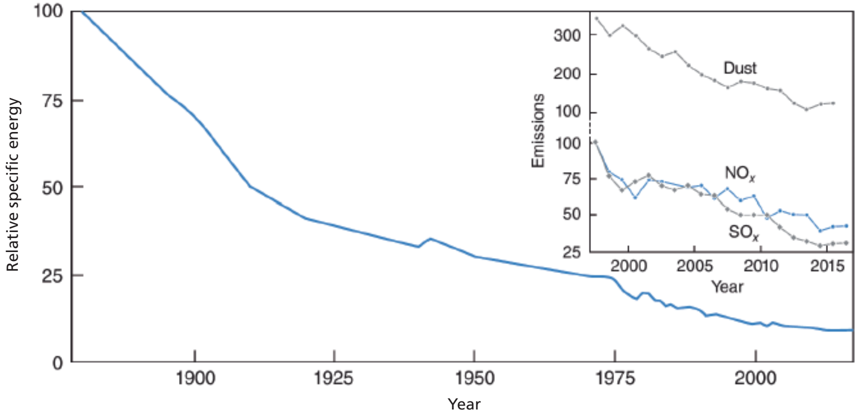


Figure 7.1. Energy efficiency gains over 150 years and NO$_x$, SO$_x$ and dust emissions for the last quarter century.

Source: http://www.agc-glass.eu/sustainability/environmental-achievements/air

Sustainable responsible glass production & climate action (UN Goal 12&13)

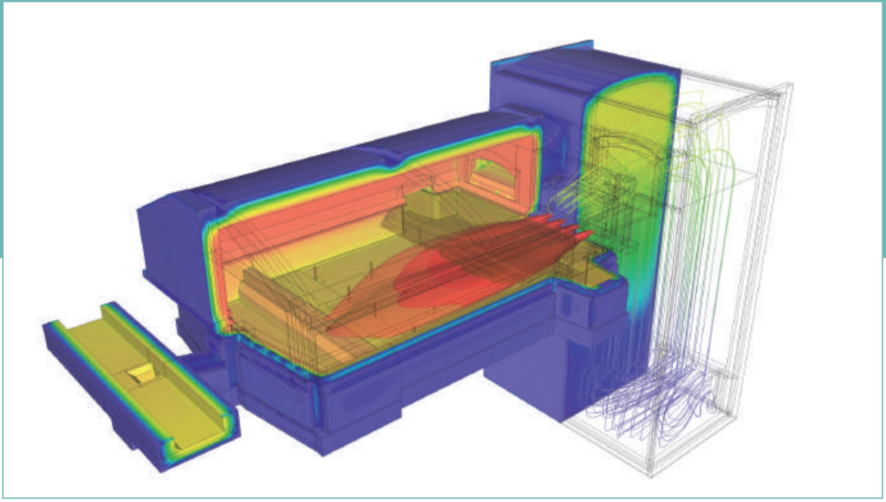
Melting glass requires considerable energy to reach the necessary high temperatures (>1500°C). Glass production used to take place in "glass houses" where people had local resources—sand and wood ash as raw materials and wood from the forest for energy. Old glass houses can still be found in forested areas. As much as 150-200 kg of wood was needed then to melt a kg of glass [4]. Assuming wood burning generates about 19 MJ/kg, this equates to >2850 MJ for a kg of glass. Today's result of 3.5 MJ/kg is astonishingly 800 times more efficient.

Over the last century, the main energy source has shifted to fossil fuels such as oil and natural gas. Modern glass melting uses about 1% of all industrial energy [5] much less than for example steel production. Nevertheless, it is energy intensive and massive improvements have been made over the years. Asahi Glass Company have plotted these downward trends, and the reduction in pollutants such as NO$_x$, SO$_x$ and dust emissions for flat glass production (Figure 7.1).

Figure 7.1 also shows that since 2000 the relative specific energy line has flattened, suggesting little improvement in recent furnace designs. Furnace efficiency had increased because new refractories allowed higher combustion and crown temperatures, and increased melting temperatures. Furnaces became larger, producing more glass per m^2 of heat loss surface. Some flat glass furnaces now produce a remarkable 1200-1500 tons/day while container glass furnaces can melt a high 800 tons/day. But furnace size is limited by the maximum crown span (width), the size of equipment, flame length, and other factors. Larger regenerators have increased heat regeneration from 50% to 70%, close to the theoretical maximum of 75%. This maximum arises from the difference in heat flow in the waste gas (greater mass and specific heat) than the air being preheated.

Figure 7.2 shows the design of the most common U flame (end-fired) container glass melting furnace,

Figure 7.2. A 350 TPD container glass melter.
Source: Courtesy of Glass Service a.s. (www.gsl.cz).



producing about 350-380 TPD (tonnes/day). Cold air enters the base of the regenerator at the right and is preheated to 1200-1300ºC, before leaving at the top and entering the combustion chamber. Gas (or oil) is injected into the hot air at the base of the port. This example has four injectors. The iso-temperature surfaces indicate the flame shape that develops. The hot gases radiate heat to the glass melt surface, the furnace walls and the crown, the latter two re-radiating energy to the glass. The waste gases then circulate round the furnace and exit via the left exhaust port, entering the opposite regenerator, and preheating it until the process is reversed after 20-30 minutes. Raw materials enter into the melting basin from two sides. First the batch under the flames is melted. Some designs have a barrier wall (0.8 m high) on the bottom of the furnace to bring the glass from a typical depth of about 1.3 m to the melt surface to aid the removal of small bubbles, the so-called fining process. The glass then dives down into the sunken throat to be delivered into the distributor which connects to the forehearth which takes the glass to the forming machines. The small rods protruding from the bottom of the glass basin are molybdenum electrodes that assist in melting the glass by electrical Joule heating, often called electric boosting. Such a melter is typically about 15 m long by 6 m wide.

The second most common glass melter is the cross-fired regenerative float glass furnace. Flat glass is formed after leaving the melter by floating the melt on a molten tin bath. This glass is mainly used for window glass or automotive windshields also solar panels or sometimes LCD products can be produced. The furnaces can be 35-40 m long and 10-12 m wide. The most typical pull rate is 600-800 TPD, but some furnaces produce 1200 or even 1500 TPD. These cross-fired regenerative furnaces alternate firing from opposite sides. They have five to nine burner ports on each side and the preheated air comes from brick regenerators on each side. Injectors introduce gas into preheated air to create flames crossing the glass melt surface, the hot waste gases exiting to the opposite regenerators. This process is reversed about every 30 minutes.

Figure 7.3 shows a 600 TPD float furnace with 5 ports with 2 gas injectors on each side. Raw materials are introduced by batch chargers. After melting, the glass is cooled in the working end and leaves by the canal onto the molten tin, where it spreads out to form a flat sheet.

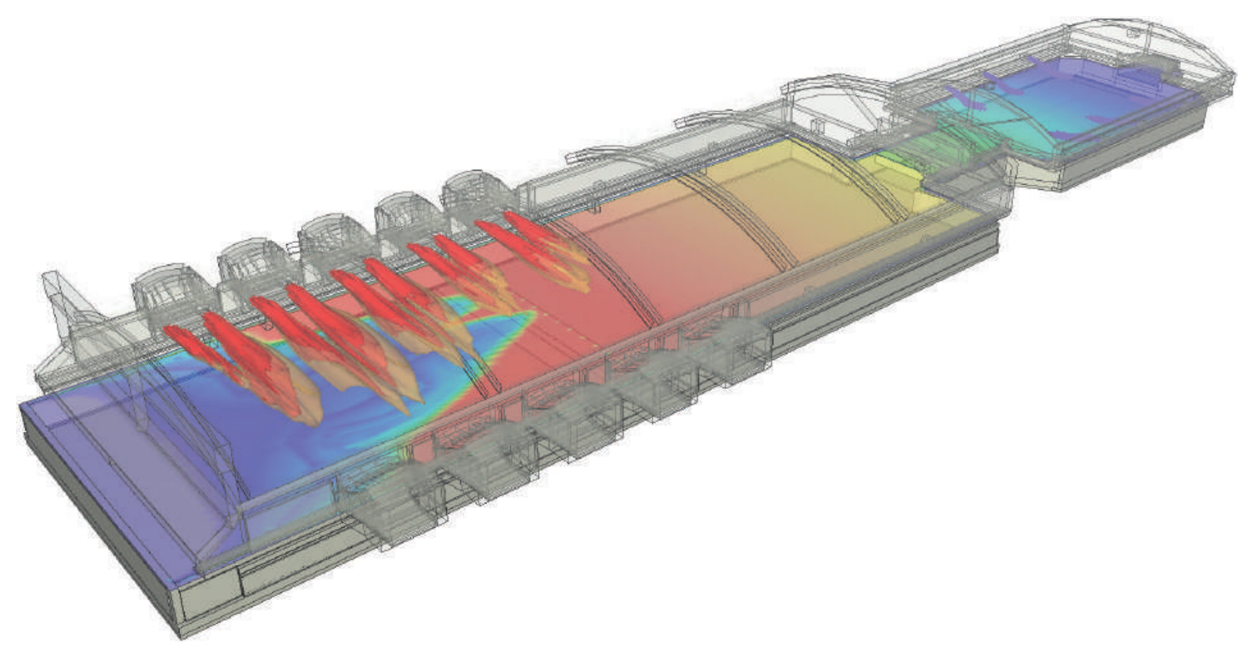


Figure 7.3. A cross-fired regenerative 600 TPD float glass melting furnace.
Source: Courtesy of Glass Service a.s. (www.gsl.cz).

Other furnace designs

Other technologies include the recuperative and the oxy-gas furnace. Oxy-gas furnaces use pure oxygen, extracted from air and may seem more energy efficient than the best regenerative furnaces. A correct analysis though requires the energy and cost of separating the oxygen be considered and usually favors a regenerative furnace. However, oxy-gas furnaces can bring other benefits - NO_x reductions and a smaller footprint. Recently, two industrial gas suppliers have reduced energy consumption by preheating the fuel and oxygen.

Linde (Praxair) developed the OptiMelt™ technology to save another 20% of energy by preheating the natural gas with waste gas from the oxymelter to create a syngas ($CO + H_2$) formed by cracking CH_4 with CO_2 in the waste gas [6]. An interesting side benefit is that CO tends to reduce foam on the glass surface, increasing heat transfer and lowering seed counts.

Air Liquide designed HeatOx technology with heat exchanging recuperators using furnace waste heat to preheat the natural gas and oxygen indirectly to 400-500ºC, giving 9-10% additional energy savings [7-9]. Should this technology be installed in a conventional regenerative float furnace converted to oxy-gas firing, a total of 20-25% energy savings may be achieved. A side effect would be a major NO_x reduction.

Finally an oxy-gas furnace is apparently converted to burn hydrogen more easily than an air-fired furnace. Burning hydrogen with air gives higher flame temperatures typically equating to higher NO_x emissions. Oxy-gas furnaces may therefore be more attractive when hydrogen is affordable.

Electric melting

The first continuous regenerative glass melting furnace was invented by Charles William Siemens of Westminster England between 1872 and 1880 and modern regenerative furnaces have changed little since.

Many do not realize though that continuous all electric melting (AEM) is almost as old as gas-fired regenerative melting. The first electric furnace was built in 1905 following French Sauvageon's design and was for window production. The specific energy consumption was even then only 0.73 kWh/kg. Many designs have been implemented since but recently electric melting has fallen in popularity due to its high cost compared to widely available fossil fuels.

Global warming and pressure on carbon footprints, has rekindled interest in full or partial (hybrid) electric melting. Alternative energy sources for electricity have helped to lower costs and production is essentially CO_2 free; for example in Germany, 40% of electricity is generated using renewable resources such as wind, solar, hydro, and bio. The question for the future is not if more electricity will be used for glass melting but what will be the balance between fully electric and hybrid furnaces (substituting bio fuel for fossil fuel).

Glass is important in generating green renewable energy, or "green electricity". Most wind turbine blades are composed of reinforced glass fiber. And most solar panels use large quantities of flat glass. In the future photovoltaics will probably be widely integrated into windows. These applications mean that glass is not only a consumer of renewable energy but also has an important role in generating it.

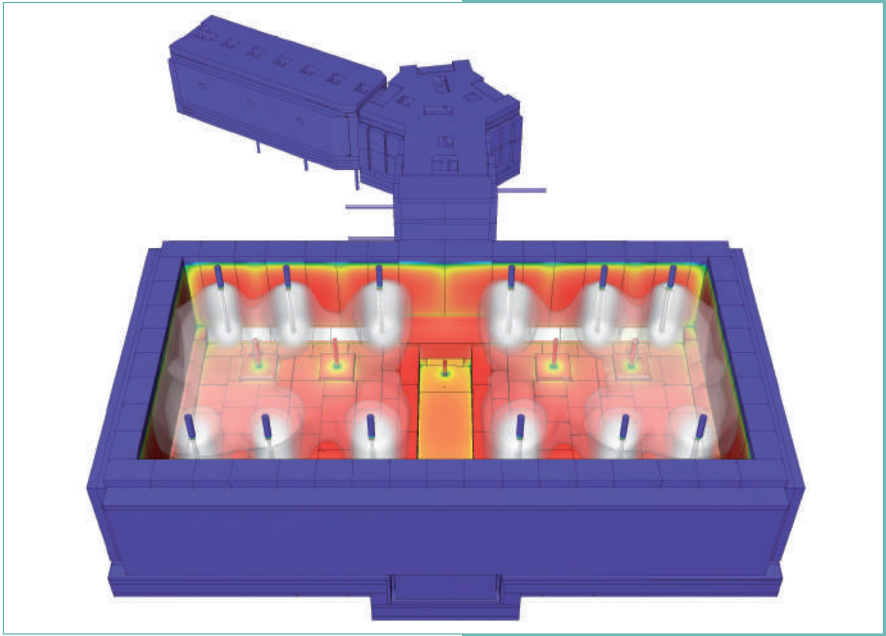


Figure 7.4. An 80 TPD cold top rectangular all electric melter using top, side and bottom molybdenum electrodes.

Source: Courtesy of IWG Wagenbauer and Glass Service.

For larger furnaces with higher pull rates, the higher volumes and lower wall losses make recuperators or regenerators sensible. Gas-fired furnaces can be cheaper than the efficient electric melter. This was historically so in most countries because electricity was generated from fossil fuels, and typically 2.5 to 3x more costly per kWh than the fuel alone.

Even small electric furnaces are 70-85% thermally efficient. While a fuel fired furnace without a recuperator at a low pull is only 10% efficient, adding a regenerator improves efficiency to 45% and an oxy-gas fired furnace, can achieve 50% efficiency.

Most common all-electric melters produced 10-30 TPD, sometimes up to 80 TPD. They were round or hexagonal to avoid heat losses via the furnace walls and to allow more easily distributed batch charging and electric connections. Figure 7.4 shows a larger rectangular melter at 80 TPD. These cold top electric melters used the batch cover as a heat insulating blanket, conserving heat inside the melt. They were called vertical melters, as the glass melts on the surface near the batch, refines at lower levels and flows out via a bottom throat into a working end/distributor. To maintain batch coverage and hence an insulating blanket, the cullet content was usually below 50%. Electric melters were mostly used for high quality clear glasses and crystal (lead) glasses, as the redox (color) control is best managed with this process.

During the 1970 global oil crisis, some glass producers, especially in the United States converted their regenerative furnaces to all electric melters. They retained the infrastructure and horizontal configuration because other shapes were difficult to incorporate into their existing space; sidewall losses are less important at higher pull rates.

The future of carbon free melting —electric, hydrogen or hybrid?

Currently, 95% of all glass melting uses fossil fuels, mostly natural gas or heavy oil; but industries are now strongly encouraged to follow the Paris Climate Agreement guidelines and are seeking to minimize CO_2 emissions. Many but not all countries are enforcing rules, with penalties for carbon emissions and benefits for reductions. Either way, the glass industry knows its consumers expect low-carbon or carbon-free production, so are working to achieve this while remaining competitive amongst themselves and with other packaging materials.

Four key technologies for carbon reduction exist, in addition to those already discussed. They are:

- Cold top all electric vertical melting (AEM).
- Hydrogen combustion (replacing natural gas in regenerative or oxy-gas furnaces).
- Horizontal hot top electric melting (H^2EM) also referred to as hybrid melting.
- Horizontal hot top hydrogen electric melting (H^3EM).

The question is: What is the best solution —not just now— but for 2030? 2050? After 2050?

Hydrogen

Currently, truly green hydrogen produced by electrolysis using renewable electric energy is the first choice, but there is simply insufficient available. Even with low electric pricing, hydrogen at 6€/kg is three times too costly to compete with natural gas. So, in most regions it would be uneconomic, without state subsidy. More research on hydrogen combustion is needed, specifically the effect on the molten glass and refractories of water concentrations approaching 100% in the combustion atmosphere. Certainly concentrations near 50% in the combustion atmosphere of oxy-gas furnaces created problems. Using electricity to break water into H_2 and O_2 by electrolysis is expensive and is only now reaching 70% efficiency levels. However, expectations are that investment costs should decline while efficiency continues to increase so that, as more renewable electricity becomes available, hydrogen will become affordable.

But why consider hydrogen? If electricity is used directly, the furnace melting efficiency is much higher than via the hydrogen route. An advantage of hydrogen is the possibility of storage for long periods, allowing long-distance transportation and creation of a buffer against supply hiccoughs. Storing electricity for similar times is simply not efficient. Unused batteries slowly lose power while storing sufficient energy would require huge batteries. Different storage options are shown in Figure 7.5; some, such as hydro power have been created but are not universally applicable, mountains and water reservoirs, as in Norway or Austria being necessary. Energy storage today is facilitated by methane which can be stored for millennia in caves with appropriate geology [10].

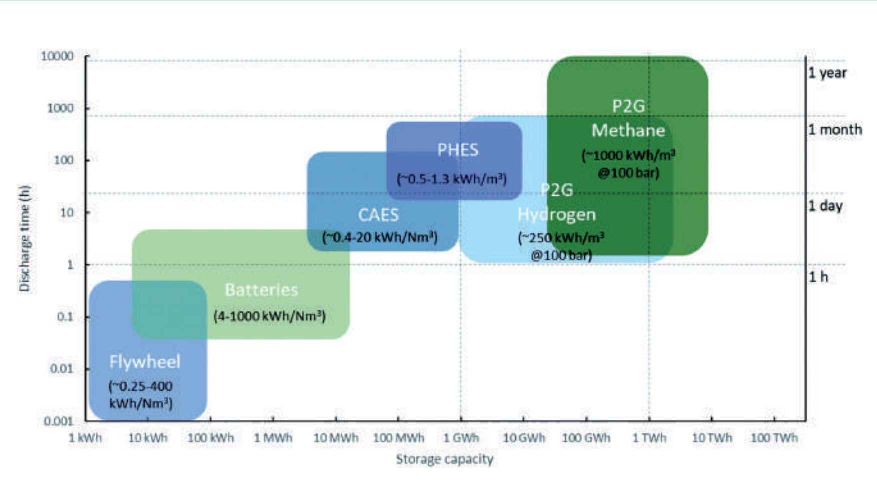


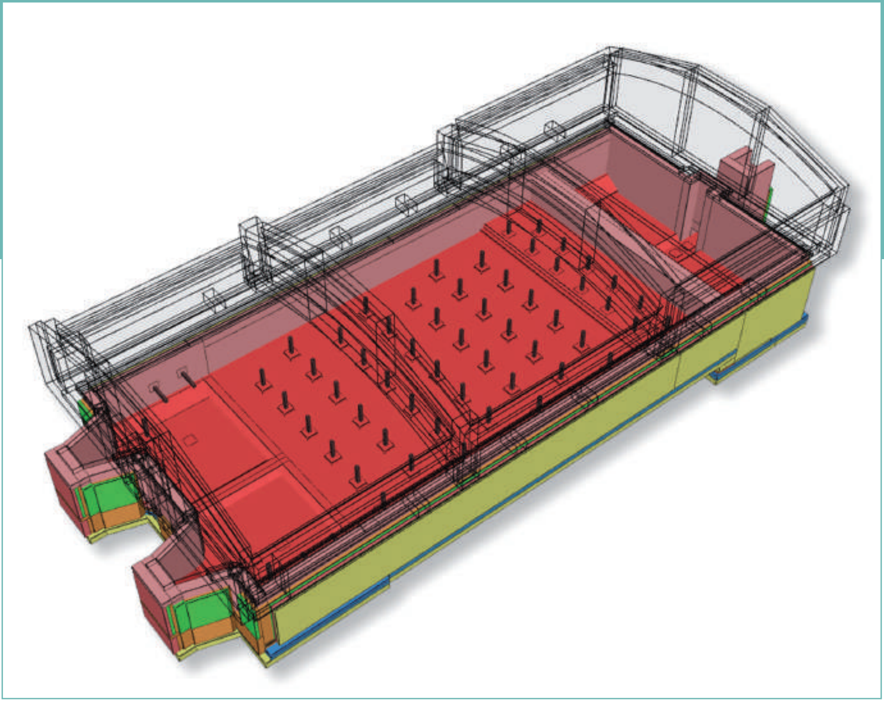
Figure 7.5. Showing the capacity and discharge times for different storage technologies.
Source: RMIT.

All-electric melting

Electric melting has been a proven technology for over a century so why not convert all furnaces to all-electric melting? Mainly because electricity typically costs three times that for natural gas /kWh. While electric melters are twice as thermally efficiency, they are more expensive to operate. Another obstacle remains. Most electric melters are producing less than 80 TPD. Only a handful in the entire world melt more than 100 TPD; and only two have produced 200 TPD —both were stopped due to production issues. All-electric melters greater than 200 TPD, have diameters so large that maintaining a well distributed insulating batch blanket across the melt surface is difficult although a key requirement for keeping the furnace operational. Should the batch cover disappear, the furnace loses heat from the top, the glass cools, melt quality and pull rate fall and production deteriorates. There is also limited long-term experience at that size of producing reduced colored glasses or melting with high cullet levels.

Figure 7.6. 3D view of the combustion space and glass melt in a Horizontal Hybrid Electric Melter at 80% electric mode and 20% firing mode.

Source: Courtesy of Glass Service a.s. (www.gsl.cz) and FIC UK (www.fic-uk.com).



Hybrid melting

Hybrid melting entered the glass dictionary in 2017 being mentioned by companies such as Glass Service & FIC-UK, Fives, TECO, Horn and Sorg. Previously discussion was limited, though hybrid melting simply means more than one heat source and has a long history. It is analogous to hybrid cars where the engine is the main power source, while the battery-driven electric motors can move the car short distances and add extra power during acceleration. Previously, electric boosting in glass production was often for 15-30% of the total energy input. Combustion is also used in hybrid melters (H^{2}EM) but 50% or more energy comes from electric heating. The thermal efficiency of the electricity is 85-90%, while combustion is about 50%.

A smaller all-electric furnace (<4 TPD/m^2) has the following advantages:

- No emissions (NO_x, SO_x) or particulate dust, so no filter or cleaning costs for waste gas.
- No chimney stack and therefore fewer complaints from neighbors.
- Lower investment: no crown, regenerator or flue gas channels.
- No regenerators to clean.
- Lower raw materials costs, because volatilization reduced.
- Lower repair costs and shorter repair times.
- Efficiency is less impacted by furnace size and capacity.

Hybrid melting restores the following advantages relative to electric melting:

- Pull flexibility.
- Reasonable furnace lifetime (10-12 years).
- Experience of operators (behaves more like a standard furnace).
- Less dependent on electrical power availability (net stability). Switch to more combustion.
- Cullet can be up to 90% of batch.
- Unchanged furnace size and aspect ratio, to match existing hall.

The ‘Furnace for the Future’ (F4F) project organized by a consortium of glass makers [11] is expected to adopt a flexible design independent of energy source, melting at times with 80% fossil fuel/H_2 and 20% electric boost (at 3 MJ/kg), or conversely 80% boost and 20% combustion (at 2.5 MJ/kg). This should reduce the risks of adopting a new technology. Figure 7.6 shows the concept design of such a horizontal hybrid electric melter.

Hybrid electric melting and oxy-gas furnace such as this can break the magic energy barrier undercutting a specific energy consumption of 3 GJ/ton of glass (with 70-80% cullet).

Table 7.1 shows that using electric energy directly in the glass melt is much more efficient than hydrogen whether by combustion or via the fuel cell. Direct efficiency is estimated to be 79%, whereas hydrogen reduces efficiency below 30%.

Renewable source	Electricity	Hydrogen electric	Hydrogen combustion
Renewable source	100%	100%	100%
Electrolyzer		70%	70%
Compressor		92%	92%
Transportation	92%	98%	98%
Transformer/fuel cell	95%	52%	
Heat losses effect (electrode holders, fluegas)	90%	90%	45%
Total	79%	30%	28%

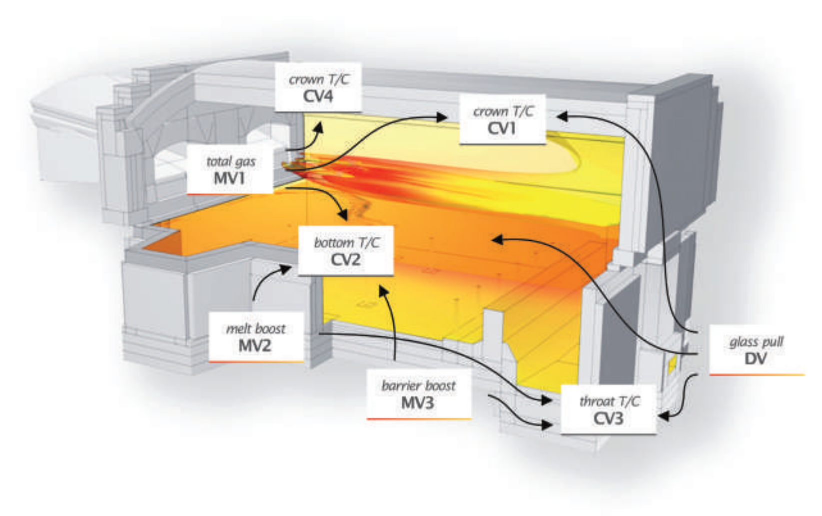
Table 7.1. Comparison of electric melting efficiency versus hydrogen route.

Dark factory with smart glass furnaces or Industry 4.0 (UN Goal 9)

Since 2020, new technologies such as neural networks have generated opportunities for automation that were impossible before. As consumers we see it first-hand in self-driving vehicles. If automation is pursued for furnaces, forehearths, and perhaps the complete production it becomes possible to switch lighting off and create so called “dark factories”.

Without doubt, the term Industry 4.0 created during a Hannover Messe in 2011 has awakened modern industry to the coming revolution. The last decade has seen the glass industry work diligently to optimize systems, but more is required. Realistically, production in 2030 will need far less human intervention than now.

Industry 4.0, often referred to as Big Data or the Internet of Things, refers to high levels of automation of individual parts of production and intimate communication between them. For example, if defect levels increase, then the system itself decides how to react. It might increase or reduce the furnace temperature, whichever is appropriate. Such decisions currently depend on human interpretation and experience. We review next the automation already used in the glass industry and investigate new technologies such as artificial intelligence (AI), neural networks, machine learning, deep learning



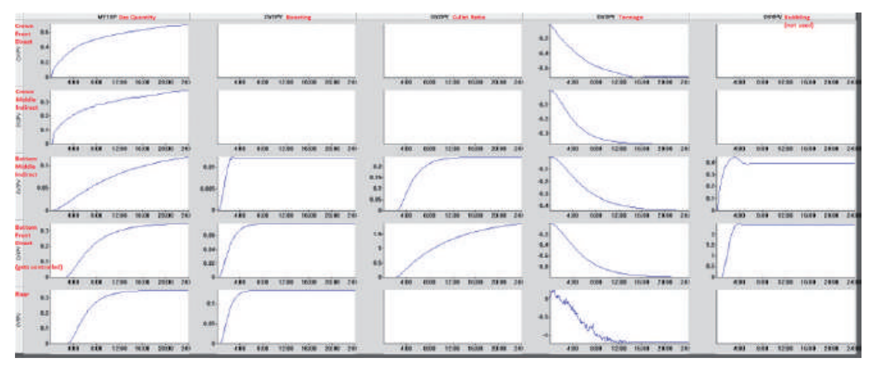


Figure 7.7A (upper). Advanced model based predictive control model relations [12].
Source: Glass Service, a.s.

Figure 7.7B (lower). Example of model relations after process identification using historical data.
Source: Glass Service, a.s.

Figure 7.7C. ESIII PC taking over with MPC furnace control from the operator.
Source: Glass Service, a.s.

and how they will impact production.

Leading engineering firms and glass producers around the world use furnace modeling known as computation fluid dynamics (CFD). While in 1990 accuracy was debated, today the technology is considered reliable and valuable. It has become state of the art for designing or rebuilding furnaces. Furnace and forehearth model predictive control (MPC) systems of today, one of which is the Expert System III™, have evolved beyond CFD. Initially sceptics had little belief that it was possible to control a furnace using MPC. Today over 300 furnaces worldwide have it installed, with over 20% of their forehearths.

Since 2010 interest in Industry 4.0 has skyrocketed, as new equipment has been installed, such as furnace cameras to monitor batch flow. The question is what next? A review of Industry 4.0 uncovers many different technologies to use and bundle together to optimize factory operation. Robots, augmented reality, the Internet of Things and Big Data, where useful information is harvested using powerful computers,

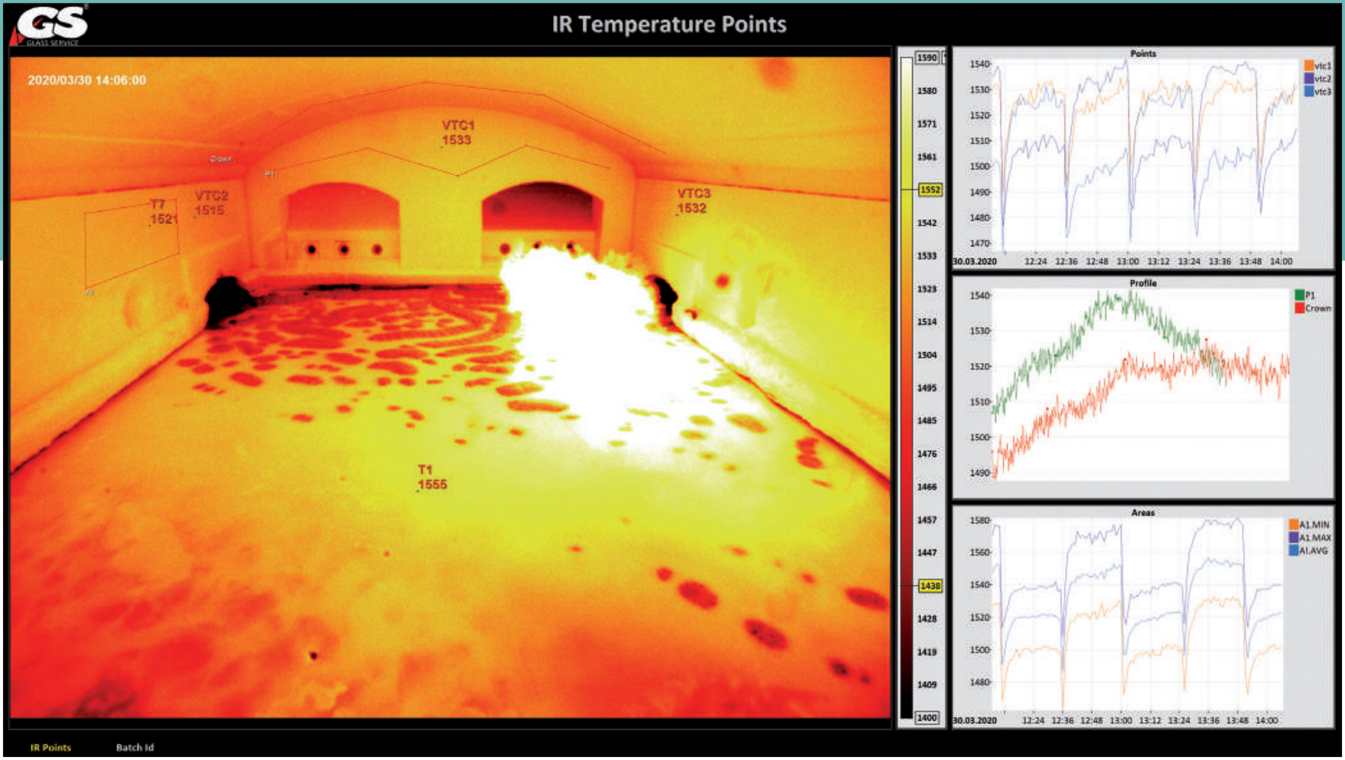


Figure 7.8. Furnace image using near IR camera.
Source: Glass Service, a.s.

all can contribute to efficient operation.

A proportional-integral-derivative (three-term) controller (PID) employs a control loop using feedback. They have been widely used in applications requiring continuously modulated control but often offer limited success because: (1) round the clock PID control by a single operator was demanding and unreliable; (2) furnace temperatures were slow to react; and (3) responses to change were subject to long dead times. MPC strategies using dynamic algorithms offer an alternative. They capture process behavior with minimal intervention while maintaining optimum quality, lowest emissions and minimal operational costs.

MPC typically works with furnace inputs such as gas, crown and bottom temperatures (Figure 7.7A-C). Mathematical models are created using software such as *Expert System III*™ and this historical data. These linear models predict the future response of a furnace.

The next step requires more complex inter-relationships to be understood. One is how temperatures relate to glass quality. Should furnace temperature be increased for better glass quality, or lowered as would be the case for re-boil or refractory reactions? Such questions showcase areas where artificial intelligence offers more than straightforward linear models.

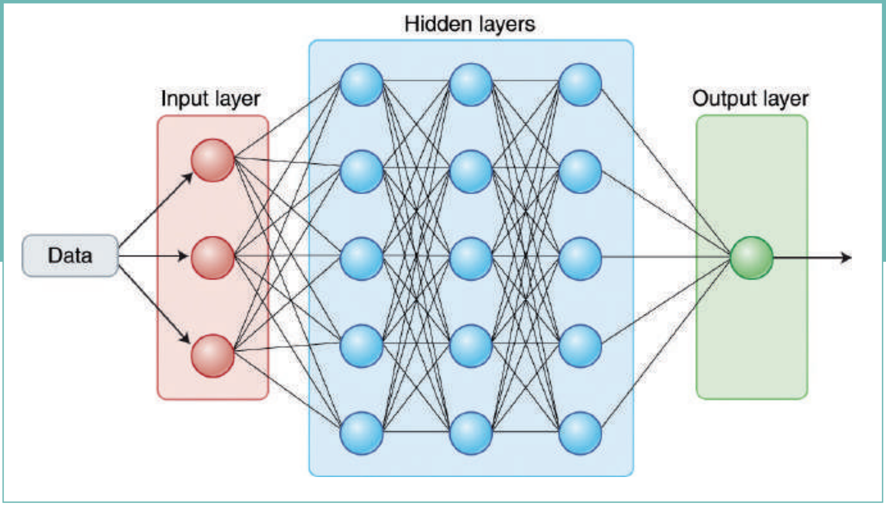


Figure 7.9. Neural networks, with deeper hidden layers.
Source: Glass Service, a.s.

Much more data is available than in the past. But, how to handle it? Near Infrared (NIR) furnace cameras can act as virtual thermocouples and see the temperature trends within the furnace over time (Figure 7.8). Indeed even temperature profiles can be explored. In the following, the capabilities of such cameras are considered first and the question of data accuracy later.

First though we consider what artificial intelligence (AI) and its neural networks are? How can they help the glass industry? Most glass operators are familiar with DCS, a digital control system for a process or plant usually with many control loops and MPC. Before AI, irregular issues evaded their operators creating inefficiencies and low-quality glass production. AI anticipates and performs the tasks that could not previously be resolved by hands-on techniques. It allows the computer to mimic human intelligence to solve a problem, using neural network decision trees trained by machine learning.

Deep learning may appear magical, but is simply a multi-layered deep neural network that handles vast amounts of information. Actually, a daily search for something on Google uses the same technology. Google suggests an answer to what you are *really* searching for. So, this is already AI.

What is a neural network? It was probably named after neurons in the human body which have similar characteristics. A data set needs first to be analyzed, and after analysis, the result is the outer layer which is its meaning. So first this data was born into the inner layer of the analysis, to be formalized and then inserted into the neural network. We then teach this neural network to fill certain highs and constants inside different neurons, to learn (with lots of data on the input side) to predict what is produced as output —and to recognize it automatically. The key thing is that we don't fully understand these neurons, and we don't *have* to understand them. They are simply filled out by giving sufficient data and sufficient output for the neurons that are going to be filled with the mechanism that they recognize best. Figure 7.9 shows the data input, the data analysis and the process output.

To illustrate these concepts, let's look at an imaging technique which we use with an NIR furnace camera. The camera software is trained to recognise the images it sees, and after time can differentiate between batch, flame, glass surface, refractory, and camera build-up. So if buildup around a camera covering a thermocouple occurs, it can no longer be used reliably. Then, input data from this thermocouple should not be applied

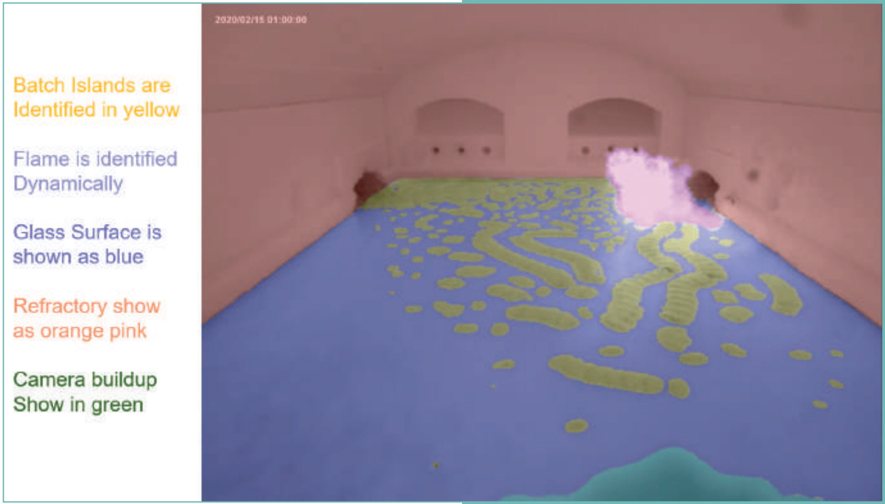


Figure 7.10. Furnace image from a camera identified by a Neural Network.
Source: Glass Service, a.s.

to deep learning. Deep learning can also detect the flame independently from the batch, determine the flame direction and signal an alarm if the furnace needs attention. With neural network technology, we can learn much more from these images than just temperatures and process them to make intelligent control decisions (Figure 7.10).

The next step is to measure the batch distribution. The image is transformed to eliminate the parallax errors caused because the camera tilts (Figure 7.11). The yellow areas represent the batch piles. In this furnace there is clearly more batch on the left than the right. Thus, the batch location coverage and movement can be monitored, facilitating corrective actions (Figure 7.12). For some furnaces, stability is vital, for others less so.

The next question is: Will there still be employed workers if AI technology is used and becomes standard? For this we look for historical data in other areas for comparison.

The great benefit of MPC is that it improves and upgrades furnace operation. There may be disagreements about its installation, caused by concerns about job security. An understanding within the factory is important to convince employees that this will not be so; instead it will assist their work. The goal is to give them new technologies which enhance production processes. Intensive and continuous training of employees is necessary to manage properly the new technology. Different capabilities and skills need to be incorporated to the workforce, a constant factor in Industry 4.0 implementation in every sector and field.

In conclusion, the perspective is to not be afraid. The artificial intelligence revolution that has arrived cannot be avoided. Some suggest that the AI revolution is much larger than any automation revolution seen before. Strong leadership skills and business practices will prepare workers, so that they can understand and accept AI, because it will revolutionize our lives and bridge the gap between what humans are capable of and what is actually possible. AI will penetrate across

Figure 7.11. Batch coverage converted into a bird's eye view.
Source: Glass Service, a.s.

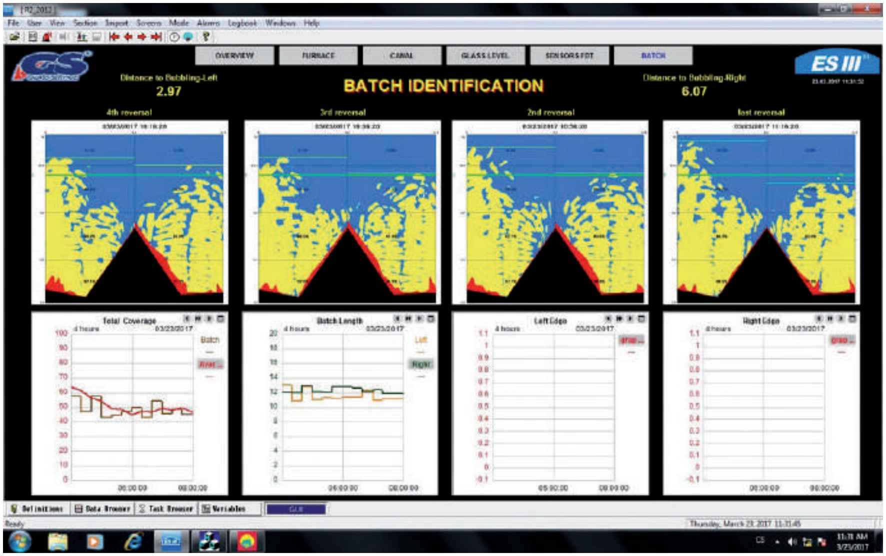


Figure 7.12. Batch coverage of about 62 m^2 over several reversals.
Source: Glass Service, a.s.

industries to take over basic tasks from humans, seamlessly interacting with our daily lives. As Elon Musk has said, we have already become Cyborgs. "If you forget your phone at home, a simple thing, you will feel helpless. Without your phone you will miss numbers, contacts, your agenda, maps, and no communication anymore, nothing to do while waiting. Who still knows the phone numbers of all the people you know inside your phone?".

Summary and outlook

With the acceptance of Industry 4.0 automation, the required 55% reduction of carbon emissions should be possible before 2030 through

- Improved glass recycling (in both amount and quality).
- Greater use of low-cost green electricity, in hybrid or all electric furnaces.
- The use hydrogen for combustion or electricity generation.

Generating hydrogen using green electricity will become important post-2030. The 2050 goal of an 80% CO_2 reduction, will require large amounts of green electricity and a functioning hydrogen economy to replace fossil fuels for glass production, and transportation to and from the factory.

Industry 4.0 automation will continue its forward progression. A dark glass factory may be difficult to imagine by 2030, but not by 2050 when the light from hot gobs falling from the forehearth spout will be all that illuminates the factory hall.

References

[1] https://www.cambridge.org/core/journals/contemporary-european-history/article/glass-recycling-container-in-the-netherlands-symbol-in-times-of-scarcity-and-abundance-19391978/D4119AC7A38C4D29486557CCACF3D4FC

[2] https://www.gpi.org/a-circular-future-for-glass

[3] https://publications.jrc.ec.europa.eu/repository/handle/JRC68281

[4] https://en.wikipedia.org/wiki/Forest_glass

[5] https://www.eia.gov/todayinenergy/detail.php?id=12631

[6] https://www.lifeoptimelt.com

[7] https://www.oxyfuel-heatrecovery.com/sites/oxyfuel_heatrecovery/files/2017/03/28/oxygen-natural_gas-preheating-for-oxy-float-glass-air-liquide.pdf

[8] https://www.lifecleanox.com/sites/cleanox/files/2018/05/30/extractpage_glass_worlwide_may-june_2018.pdf

[9] https://www.ecoheatox.com

[10] https://patents.google.com/patent/US230668A/en

[11] https://feve.org/about-glass/furnace-for-the-future

[12] Glass Service, a.s. data, with Gob Input Data from Cortex.

MICHAEL DELLE SELVE

8. Sustainable Glass in a Circular Economy

WE all strive for a better tomorrow —a world where the planet and people are healthier and happier than they are today. In the face of global warming, public health crises and economic turbulence, that future has never felt more uncertain. But people are demanding more from businesses, governments and one another to ensure we foster a more sustainable world for the next generation. In such turbulent times, it's reassuring to know that for product protection, one aspect of our future is clear: glass packaging. The timelessness of glass means the packaging people have loved most, yesterday and today is the very best option for tomorrow.

For close to two millennia, glass has been a touchpoint of celebration, commerce, culture, and science for societies around the world —its footprint shaping local communities stretching from production lines in industrial towns, to the secretive medieval guilds of Venice's Murano, all the way back to the Romans' discovery of craft glassblowing. The simple, inert combination of sand, soda ash and limestone is a formula that's worked its magic for thousands of years, and it's very much here to stay, according to the research *'Glass recycling, an activity that continues for millennia'* [1].

Yet there's another element that goes into the mix, and as society turns its attention to issues of circularity, responsible production and consumption and environmental impact, it's coming to the forefront now more than ever. It's an ingredient that's just as important as any of the natural raw ingredients: recycled glass.

When it comes to ensuring sustainable consumption and production patterns and fostering sustainable cities, glass is in a class of its own. Glass is the only packaging material which is not just reusable and refillable, but also infinitely recyclable in a closed bottle-to-bottle loop. What does that mean in real terms? That bottle of wine you're saving for dinner tonight may have started its life as a six-pack of beer, a jar of jam, or even a pot of face cream. And if you make sure to drop it off at the bottle bank afterwards, it could be back on the shelves living a whole new life in as little as a month.

That's because the same glass material can be indefinitely reused without any loss of quality and recycled again and again into new bottles and jars. Once produced, a glass bottle becomes the main resource needed to produce new bottles —meaning the more recycled content that can be used, the more we can reduce our need for virgin raw materials. And all of this adds up to lowering energy and CO_2 emissions, crucial if we want to keep global temperature rise to well below 2ºC in line with commitments to the Paris Agreement and the 2030 Agenda for Sustainable Development.

All of this makes glass unrivalled in its environmental credentials. Join us as we look deeper into the miracles of glass, and what it represents for planet, people, and society, as we work towards a circular economy that works for all.

A circular economy that works for the good of the planet

There's nothing like glass when it comes to packaging that's both reusable and infinitely recyclable. With endless lives, glass can be recycled again and again, in an endless loop, into new bottles and jars. And recycling rates are at a record high: today, 7 in 10 glass bottles are collected for recycling in the EU, which is a global leader in household recycling with collection systems that have been perfected over decades.

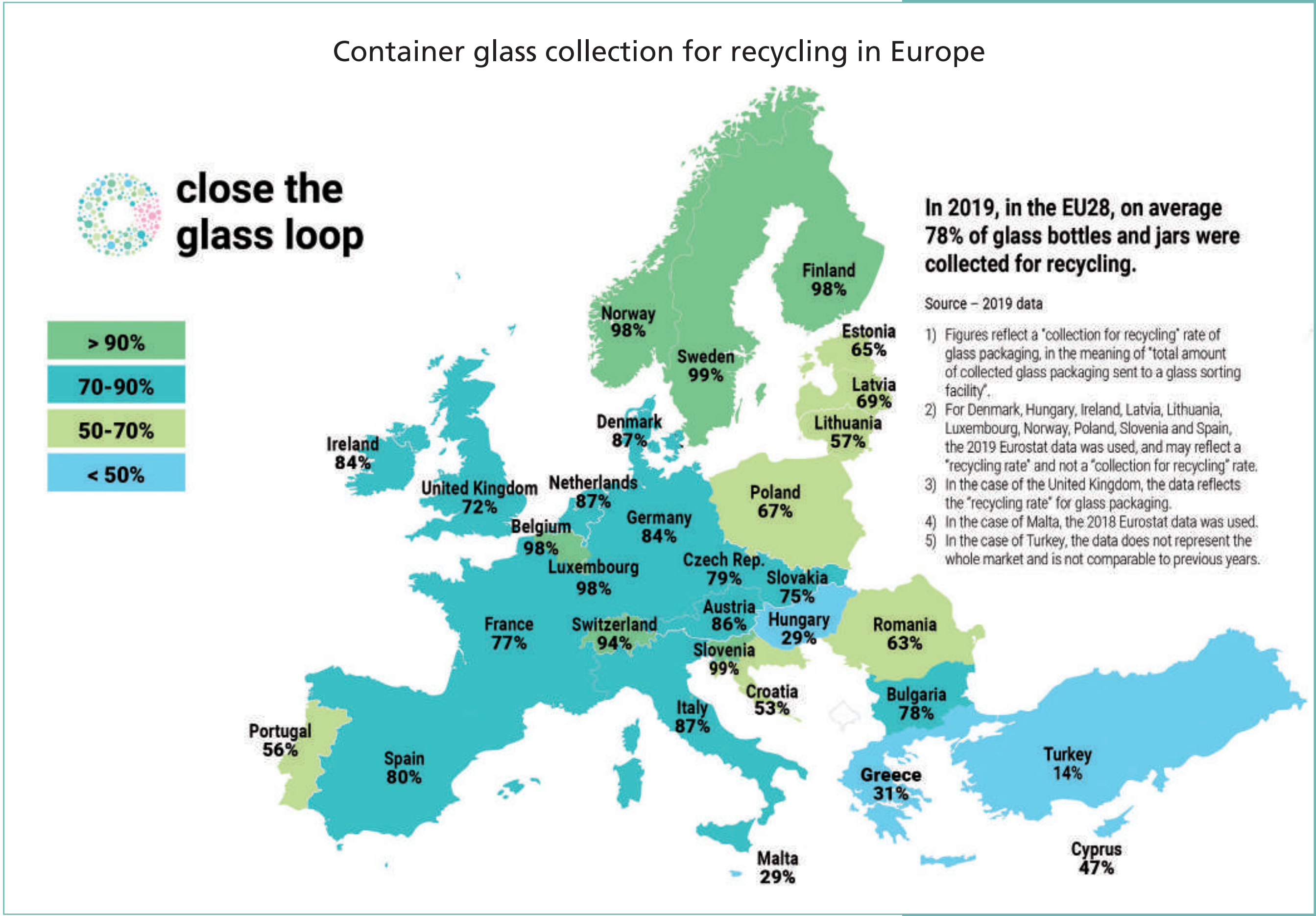
Yet it may surprise you to learn that despite its recyclability, the inherent properties of glass do not become corrupted over time. Again and again, glass can be made a new using recycled content along with the natural raw ingredients, and new bottles and jars will be just as high in quality as older products. All of this makes glass a permanent material —ideal to maintain a true circular material loop. Due to the strength of their chemical bonds, permanent materials are not damaged by the recycling process and can stay in the recycling loop indefinitely, as long as they are properly collected, treated and re-melted.

Today, a record 78% of all container glass put on the market in Europe is collected for recycling. For a breakdown by country, see Figure 8.1 and through the link with the latest available data [2].

And the industry wants to collect more and better into the bottle-to-bottle production! Close the Glass Loop [3], a multi-stakeholder partnership, brings together the glass packaging value chain with the shared objective of achieving a 90% average EU collection rate of used glass packaging by 2030 and improving the quality of collected glass so that more recycled content can be used in a new production loop.

It is important however to point out that not all kinds of glass materials can be recycled into a closed loop. Soda-lime glass is the composition used for the majority of glass containers put on the market and is perfectly recyclable into new bottles. However, other compositions such as crystal glass must not be collected into bottle banks because it can't be recycled —in fact, this kind of glass can actually contaminate the entire glass recycling process because it may contain lead.

Glass bottles are available in a large range of colors, but only three are mainstream and represent the vast majority of the bottles on the EU market: flint (transparent), green and amber glass. Color choice depends upon several factors, ranging from aesthetics to UV-resistance —yet color separation is an important step in recycling, to ensure that all glass collected can be recycled, depending on local specificities like production versus consumption. This color separation can take place either at


Container glass collection for recycling in Europe

In 2019, in the EU28, on average 78% of glass bottles and jars were collected for recycling.

Source – 2019 data

1) Figures reflect a "collection for recycling" rate of glass packaging, in the meaning of "total amount of collected glass packaging sent to a glass sorting facility".
2) For Denmark, Hungary, Ireland, Latvia, Lithuania, Luxembourg, Norway, Poland, Slovenia and Spain, the 2019 Eurostat data was used, and may reflect a "recycling rate" and not a "collection for recycling" rate.
3) In the case of the United Kingdom, the data reflects the "recycling rate" for glass packaging.
4) In the case of Malta, the 2018 Eurostat data was used.
5) In the case of Turkey, the data does not represent the whole market and is not comparable to previous years.

Figure 8.1. Latest available data on the levels of container glass recycling in Europe.
Source: www.closetheglassloop.eu

source, where different bottle banks are offered to consumers to dispose of their bottles according to their colors, or after collection, through an industrial sorting using selective optical sorting machines which sort by color. Notably, once glass has been sorted by color, there is no limitations in terms of recycling to make new colored bottles: Europe boasts colored bottle production of over 90% of cullet. All green, amber and flint bottles can be infinitely recycled in a closed loop, and as glass is a permanent material, there is no degradation of the

Figure 8.2. The Close the Glass Loop partnership brings together members of the glass value chain with the objective of more and better-quality recycling in Europe through each stage of the recycling journey.
Source: FEVE.

physical and chemical properties of glass during the recycling process. Various tints of the two basic colors (amber and green) exist and pose no issue from a recycling point of view. Moreover, these tints are generally standardized (for green bottles, the most common tints are Georgia green, emerald green, champagne green and dead leaf green). Tints outside the standardized specifications are relatively rare and can be easily diluted in the mass of mainstream glass.

The environmental benefits that this continued cycle can bring are exponential. Today, glass producers use more recycled content than virgin materials in our packaging: on average, 52% of the raw materials we use are made up of recycled glass. This is crucial to meeting UN goals on Responsible Production and Consumption, because compared to producing new glass from raw materials, every ton of recycled glass used in the furnace avoids the extraction of 1.2 tons of virgin raw materials. What's more, every additional 10% of recycled glass in the furnace reduces the CO_2 emissions by 5%, while also cutting back on energy consumption by 3%.

At the center of this endless cycle? A strong commitment to recycling in cities and towns around the world, both by individuals and by industry and the wider glass value chain. Recycling glass is a topical issue in modern societies all over the world, given the continuous increasing consumption and the recyclability of glass, but it's nothing new: glass packaging and its recycling has been an integral component of human lifestyles for millennia. Historical and archaeological evidence demonstrates that even in antiquity, glassworkers were already collecting and reprocessing broken glass into new consumer goods. Looking to the modern era, the current glass collection schemes in Europe have been in place for over fifty years, and today, some 1.5 million bottle banks are available for residents to rely on.

For decades, glass has been successfully collected for recycling via kerbside and bottle bank collection across the EU, under so-called 'Extended Producer Responsibility' (EPR) schemes, backed by a strong European policy framework that lays down key waste management principles (including the waste hierarchy), sets recycling targets for all packaging materials, requires separate collection of packaging waste, and introduces the EPR concept. Centre to this framework is the Packaging and Packaging Waste Directive (PPWD) —currently under legislative review and set to be updated as part of the flagship EU Green Deal and Circular Economy Action Plan that calls for further action on packaging waste prevention, reduction and recycling.

As more and more people move to towns and cities —68% of the world population is projected to live in urban areas by 2050, according to the UN— glass recycling is set to become a model circular economy for sustainable cities to learn from. Europe currently has the world's highest recycling rate at 78%, underpinned by an extensive network of curbside or local collection systems. From that, most of the bottles recycled "close the loop" as they are broken down, refined and made into new glass products —while other waste glass may be used as asphalt in road construction, as insulation in homes, or even as a soil replacement in hydroponic food set-ups. Thanks to these collective efforts, we can prevent some 9 million tons of CO_2 from being emitted per year. Whether it's collected from a curbside or dropped off at a neighborhood bottle bank, increasing the number of bottles and jars that are collected is vital for glass manufacturers to cut back on raw materials and drive forward a circular and sustainable economy.

What's more, as well as being infinitely recyclable, glass is the only packaging that's both reusable and refillable. To further close that gap and work towards sustainable cities around the globe, we also depend on returnable (and refillable) packaging, which can be reused dozens of times and still be recycled at the end of its life. This makes glass a permanent material that forms an endless loop. Technically, we could produce more recycled material, but are limited by availability and quality. That's why as an industry, we're strongly committed to working in partnership with our members, policymakers, academics, all parts of the supply chain and other stakeholders to identify powerful and practical solutions to improving our contribution to sustainability.

Supporting consumers to make the sustainable choice

Consumers themselves are an important part of the equation. We all have a footprint through the choices we make each and every day. We're expanding our efforts to promote responsible production and consumption through consumer education campaigns, notably with Friends of Glass [4] —a pan-European consumer awareness platform with a footprint in 13 countries, to promote all the reasons why people should opt for products in glass packaging. Bringing together a community of self-confessed glass lovers, Friends of Glass campaigns encourage consumers to choose and recycle glass

Figure 8.3. Friends of Glass brings together consumers around Europe, united by a shared love of glass packaging for its environmental, health and design credentials. To date, Friends of Glass campaigns have reached millions of consumers since launch: in 2020 alone, our content gained over 13 million views on social media.
Source: FEVE.

packaging and see it as the first choice for a sustainable everyday packaging material. Our campaigns have featured everything from talking dolphins, to hidden celebrities, from singing influencers to anthropomorphized glass bottles!

We're also set to launch a new packaging symbol —known as the Glass Hallmark [5]— to better engage in sustainability conversations with consumers. Throughout history, hallmarks have been used on valuable metals to visually identify high quality products, and we see no reason why glass should be the exception. Our new hallmark incorporates all the unique features of glass that make it a high-quality, sustainable packaging material. Designed to be printed on labels or directly onto the glass itself, the hallmark highlights environmental and health benefits of glass products at a glance. Our message to the world is simple: glass is caring. Choosing glass protects the health of the environment and more importantly, ourselves.

Figure 8.4. The new Glass Hallmark stands as a symbol of what glass brings to people, planet and society. Each element symbolizes the commitment we make when choosing glass: a commitment to use resources wisely, to recycle, to protect and to work towards a more sustainable future.
Source: FEVE.

A natural circular material that works for all people, where planet and health credentials intersect

When we talk of responsible production and consumption, it's impossible to mention the recycling credentials of glass

Figure 8.5. Glass is inert and keeps products safer for longer —making it the natural choice for preserving not only the quality of the product, but the health of the people who use it.
Source: FEVE.

packaging without also touching on its health benefits: namely, that glass is the only food-grade packaging material that can be endlessly recycled into new packaging solutions without ever losing its inherent properties in terms of taste and quality preservation.

That's because glass is an inert material that does not change or leach over time. Made of natural ingredients, there is no risk of harmful chemicals getting into food or drinks that are packed in glass, and products are preserved for longer in glass, even once opened —no additional barriers or additives needed. It's also a single-layer material, which means there is no need for additional internal chemical liners such as plastics found on other packaging materials that can interact with food and beverages. For these reasons, it's also recognized as safe by international authorities, being both exempt from EU REACH chemical regulations and the only widely used packaging material considered 'GRAS' ("generally recognized as safe") by the

U.S. Food and Drug Administration. And because it's made entirely of raw materials found in nature, glass cannot pollute the environment, now or ever. All of this makes glass the natural choice for preserving not only the quality of the product, but the health of the people who use it.

In short, as an everyday packaging material, glass is natural, sustainable, and safe —crucial at a time when society is facing unprecedented uncertainty, fueled by global health and environmental crises, and when the health credentials of packaging are becoming more important to people than ever. Wellness and 'zero waste' lifestyle trends are also rapidly changing how we produce, purchase, consume and dispose of our everyday products. People are increasingly in search of a toxin-free circular economy, one that uses safe materials for food contact without losing sight of the need for recycling potential. Recycling should be part of achieving a circular economy, but never at the expense of health, and this is where glass is ready to shine.

Backed by industry initiatives for a better future

Glass already has strong environmental credentials in a circular economy and consumers are increasingly recognizing that, but that doesn't mean we're resting on our laurels. The industry is working to make glass production even more sustainable and taking rapid strides to become carbon neutral and maximize our use of recycled content. We're committed to the UN 2030 Sustainable Development Goals (SDGs), and by driving forward the transition to a resource-efficient and low-carbon economy, we'll be able to ensure that glass manufacturing can continue to thrive sustainably in the long run.

Glass is healthy, reusable and infinitely recyclable, "it the hidden gem in a carbon neutral future", as stated by *Nature* —the international journal of science [6]. By addressing our biggest problem —the CO_2 footprint produced by an energy-intensive industry —the glass industry can offer a future-proof packaging that is healthy, circular and climate-neutral— one that can sustainably meet growing consumer demand. That's the rationale behind the Furnace for the Future (F4F, for short) [7] a pilot furnace project designed to reduce carbon emissions by up to 60%. The Furnace for the Future project underpins the industry's ambition for climate neutrality and offers a clear pathway to decarbonize an energy-intensive process.

At present, 80% of production emissions in the glass industry come from combusting natural gas to melt glass. Our aim with the Furnace for the Future is to cut direct furnace CO_2 emissions by 60%, as gas is replaced with renewable electric alternatives with a low carbon footprint. We already know that electric melting works, but we're currently limited to small-scale furnaces that can only handle clear glass with limited recycled content. Put simply, that's not going to cut it if we want to produce sustainably at scale.

Enter the Furnace for the Future, set to enable larger furnaces to process all colored glass at the same time as using high amounts of recycled product. Each ton of glass recycled can save 580 kg of CO_2 —both cutting emissions and reducing landfill waste. Europe alone produces an estimated 35.85 million tons of glass each year, so imagine what that could add up to in energy savings over time, if we replace every ageing furnace with a climate neutral alternative? The furnace is the first of its kind in the world and represents the joint efforts of 19 companies (together, representing 90% of production in Europe) who have joined forces to finance the F4F for the benefit of the whole European container glass sector. The first F4F is set to be built in Germany, while the know-how from this initial pilot will be shared across the whole sector —sending a strong signal of the industry's collective commitment to improve society. A more detailed discussion on this furnace is presented in Chapter 7.

The Furnace for the Future is the pinnacle of the container glass industry's efforts towards climate neutrality, but it's by no means the end of our ambition. As an industry, we're constantly improving our energy efficiency and resource management through sustainable innovation. 610 million Euros is invested each year on decarbonization, energy efficiency and upgrading our 160 EU plants —adding up to 10% of annual operational and maintenance costs. The industry is also investing in other areas of sustainability— from making more lightweight products to decoupling emissions from production. These efforts are paying off: while glass production continues to grow, energy consumption has been reduced by almost 50% in 40 years; meanwhile CO_2 emissions are down by 70% in 50 years. We've even created the world's lightest beer bottle —a 330 ml container that weighs just 155 g!— that performs identically to heftier products.

Our shared circular economy ambitions don't stop at production. Glass is a key resource for achieving a thriving, circular European society, and the industry —a longtime leader in circularity— is convening stakeholders across the entire glass value chain to Close the Glass Loop and make our circular economy work better for sustainable towns and cities.

An action platform for a healthier planet, we want to achieve 90% average EU collection rate of used glass packaging by 2030 (up from the current average of 78%) and unlock better quality of recycled glass, so more recycled content can be used in a new production loop. We aim to do this by collecting more and better glass upfront, involving everyone who interacts with glass, at all parts of the value chain —from the glass producer to brands and consumers, Extended Producer Responsibility and Waste Management Schemes to municipalities. That's why we're bringing them all together with a common goal: to increase the quantity

Figure 8.6. Building on a longstanding cultural heritage of glassmaking dating back thousands of years, the container glass industry is continuously innovating to contribute to thriving local circular economies.
Source: FEVE.


ORGANIC

and quality of available recycled glass —so that people don't just recycle but recycle more and better. By recycling more and better, we can progress on new EU 2030 recycling targets and the UN SDGs, achieving sustainable growth opportunities in the Circular Economy.

Local by nature: a material that gives back to society

Glass is a key resource for achieving a thriving, circular society. Our industry has long been a leader in circularity, and we're committed to working with our partners throughout the entire ecosystem to meet even tougher targets. We have and will continue to work in partnership with the complete value chain to keep evolving. From energy and raw material suppliers, through waste management stakeholders, to policymakers, NGOs, and civil society at-large, we strive to find any and all approaches to enable and optimize our Circular Economy. The way we see it, a circle isn't just a shape. It is a symbol of continuity —of permanence. Glass is here to stay, and our goal is to ensure that glass continues to be seen as the leading sustainable material for healthy, reusable and infinitely recyclable packaging.

As society moves to a new age of industrialization, the glass industry also remains committed to building on its longstanding cultural heritage in cities, towns, and local communities across the world to drive sustainable growth for society as a whole. Glass production is a local industry by nature —in European countries alone, more than 125,000 people work in the glass packaging industry, spread across 162 manufacturing plants in 23 countries alone. That's why glassmaking is adapting and innovating to secure the future of the industry —the jobs that come with it and essential sectors that depend on it— and ensure glass is fit for the circular and climate-neutral economy Europe's 2050 sustainability targets will bring.

In an increasingly unstable global environment, making progress against the SDGs is not merely an option: it's a business and societal imperative for all of us, no matter where we are located. As a result, we are strongly committed to working in partnership with our members, policymakers, academics, all parts of the supply chain and other stakeholders across the glass industry, to identify powerful and practical solutions to strengthen our contribution to sustainability, and to continue to foster responsible production and consumption.

As the world continues to strive towards meeting the 2030 Agenda for Sustainable Development, the container glass industry will not rest on its laurels: we will continue to improve on our record in existing areas and continue to innovate to further sustainable practices and the well-being of the world. Glass is a natural choice for helping the world achieve sustainability targets by 2030, 2050 and beyond. It's the future, made clear.

References

[1] https://feve.org/wp-content/uploads/2019/07/FEVE-report-with-illustrations-and-hyperlinks.pdf
[2] https://feve.org/glass_recycling_stats_2018
[3] https://closetheglassloop.eu
[4] http://www.friendsofglass.com
[5] http://www.glasshallmark.com
[6] https://www.nature.com/articles/d41586-021-02992-8
[7] https://feve.org/about-glass/furnace-for-the-future

Jessamy Kelly

9. Social, Cultural and Environmental Sustainability within the International Art Glass Movement

Since their publication in 2015, the world has reflected upon and used the UN Sustainable Development Goals (UN SDG) as a target to revise our actions and to direct our research drivers with an aim to implement them by 2030. This call to action is a collective, universal wake-up call: to end poverty; to protect the environment; to achieve gender equality; to ensure health and well-being; and to ensure peace and prosperity for all. But what does this mean in terms of Art Glass? The far-reaching effect of these goals when viewed through the lens of the international Art Glass movement is an engaging and exciting space to examine. Understanding how the goals can or have been applied to contemporary art glass practice, education and community is an important enquiry for the sector. As an artist and academic educator within the Art Glass community, the UN SDGs have been an important reference point. This essay will focus on the effect of goals 4, 5, 12 and 13; which can be seen in action as a form of social commentary within the international Art Glass movement.

UN Sustainable Development Goal 12 Responsible Consumption and Production

Global consumption and production have a huge destructive impact on the natural environment and resources of the planet. Over the last 100 years, our environment has been seriously impacted and damaged by social and economic progress, risking our future development and threatening our existence.

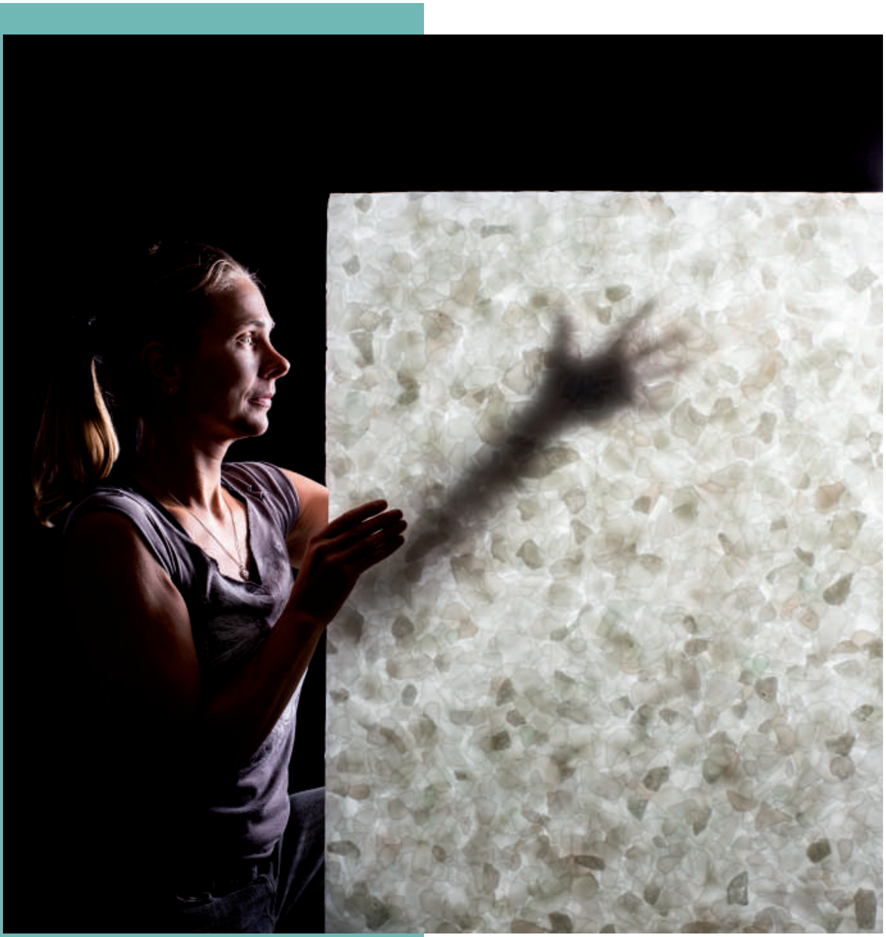


Figure 9.1. Tyra Oseng-Rees, recycled waste glass panel, 2019, 92 x 70 x 1.5cm.
Source: Johan Butenschøn Skre.

UN Sustainable Development Goal 13 Climate Action

Climate change is widespread and its affects are apparent worldwide, affecting and disrupting economies and lives. Our weather, climate and environmental conditions are changing fast. Weather patterns and temperatures are mutable, our sea levels are rising, and extreme weather events such as precipitation, drought, or flooding are widespread

Substantiality is gaining considerable ground within the Art Glass community. Glass recycling can be traced back to the first Millennium AD. Today it is viewed as a sustainable material, as it is made from natural materials and if properly cleaned and sorted can be infinitely recycled. Unfortunately, recycling and processing glass is complex. Contamination and sorting are a huge problem, most glass is only considered for single loop recycling, with the majority becoming aggregate within road surfaces. When processed and disposed of in the right way glass can offer a viable alternative to synthetic materials, offering sustainable products that actively reduce our impact on the environment. This recognition of sustainable models of practice alongside discussion of its importance within Art Glass has seen a range of glass artists prioritising sustainability as part of their practice.

In 2021, the Society of Glass Technology invited Colin Brain, Tyra Oseng-Rees, Hannah Gibson, Inge Panneels, Juli Bolaños-Durman and Gregory Alliss to speak on a History and Heritage panel focused on ‘Glass Reuse and Recycling through the Ages’. Colin Brain gave a fascinating keynote lecture about the historical perspective of

Figure 9.2. Hannah Gibson, ‘A Shattered Past’, 2021, kiln cast recycled glass, 4cm, 9cm, 27cm, 41cm.
Source: Alick Cotteril.

recycling, reminding us that recycling is not a contemporary phenomenon and dates back to early Roman glass making, with evidence that most Roman glass was recycled or reused. The Norwegian glass artist Tyra Oseng-Rees discussed her work, which she creates by upcycling recycled glass bottles into a sustainable material for wall panels and tiles for bespoke interior and architectural projects. Her work has a beautiful marble-like finish as the glass has gone through a crystallisation phase in the firing (Figure 9.1).

British glass artist Hannah Gibson discussed her figurative casts, which are part of a growing series of work called ‘Recycling Narratives - Whispering Sweet Nothings’. She first started working on this series in 2015 as a way to start a commentary on recycling and sustainability and to explore where glass comes from and the transformation it can make. ‘Shattered Past’ (2021) is a set of iconic kiln cast glass figures which are made from recycled car windscreen glass (Figure 9.2).

Figure 9.3. Inge Panneels, 'Material Journey', 2018, cast glass boat with a rubber plughole atop a fused glass wave, with poem text in the background.
Source: Inge Panneels.

Belgian glass artist Inge Panneels was able to introduce her approach, including her artwork *Material Journey* (2018), which is a social commentary on the Anthropocene, a concept which states the major geological impact humans have had on the planet's climate and ecosystems. Her work asks us to explore the impact that we have as makers. Panneels calculated the carbon footprint of her artwork to detail the energy that went into the creation of it (Figure 9.3).

Costa Rican Glass artist, Juli Bolaños-Durman repurposes found glass objects which she transforms into artefacts; each tell a unique narrative (Figure 9.4). She is based in Edinburgh and completed her MFA at Edinburgh College of Art in 2013.

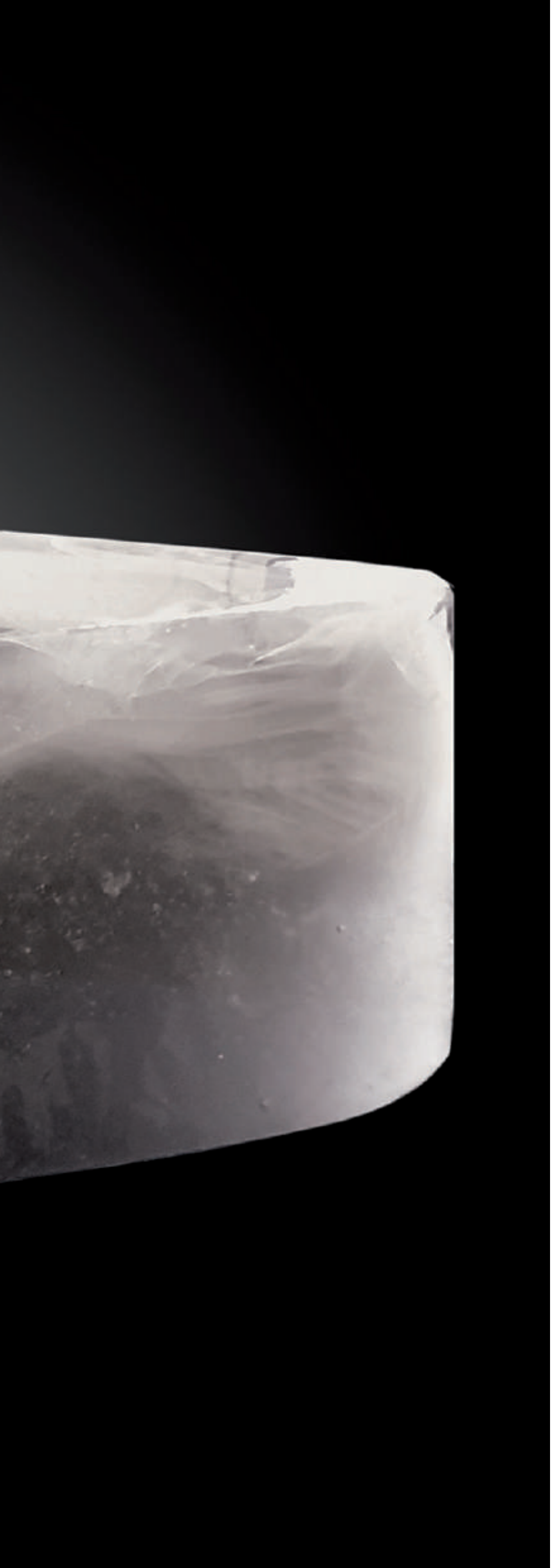
Finally, British Glass artist Gregory Alliss shared his working approach and a range of kiln cast sculptures made from recycled cathode ray tube (CRT) television glass (Figure 9.5). He is currently studying towards his Ph.D at Edinburgh College of Art, exploring sustainability in studio glass practice. His work is a strong commentary on the impact glass studio practice has on the environment as well as questioning the materials we use. His research is focused on finding low-impact alternatives for casting and for creating refractory moulds, to advance a more sustainable studio practice.

During their 2021 conference, the Glass Art Society organised 'Trace' the Virtual 2021 Green exhibition exploring sustainable glass art. The theme was devised to showcase the impact that many glass artists have on the social commentary around sustainability within glass art practice. The work of 30 glass artists was shown online [1], including work by British artist Abigail Reynolds, who created a film about making glass from locally sourced materials. She collected kelp that she made into ash to create a flux that could be added to beach sand, which she melted in a hand-built furnace to make glass. Other notable artists selected were Korean glass artist Min Haeng Kang, she transforms leftover waste by rearranging it into cell forms, and American glass artist Christopher Kerr-Ayer, who uses found and ready-made objects which are cold assembled (without heat) to create his artworks. 'Waste Glass Landscape', is a piece of my own work,

Figure 9.4. Juli Bolaños-Durman, 'Wild Flowers Collection', Collaboration x Jorum Studio, 2019.
Source: Shannon Tofts.

Figure 9.5. Gregory Alliss, Transparent Flow, kiln cast CRT Glass, 2019, 14 x 26 x 10cm.

Source: Lauren Puckett.



which was included in the exhibition. This series is concerned with the effect human activity has on our climate and environment and the impact our processes and materials have on our landscape. The piece is recycled waste glass and is concerned with material reuse. The opaline effect is a form of crystallisation in the glass that creates an opaque quality in it (Figure 9.6).

Sustainability drivers within the international Art Glass community are now high on the agenda; glass artists continue to pioneer the use of recycled and sustainably sourced materials or to develop low-impact alternatives. The small batch, limited edition and one-off production runs of glass are not over-consumed, they are conscious, deliberate and intentional acts. Production is closely connected to the glassmaker; they often make to order and take great care and time over their work. Glass Art inherently contributes to the *slow movement*. Glass Art does not cause major environmental pressures, it creates artefacts of legacy that will outlive their owners but most importantly, it can become activated as a vehicle for glassmakers to voice their concerns of the sustainability issues we face, in the form of craft-activism. Sustainable art glass production can be viewed as a vital antidote to the environmental issues we face.

SDG UN Sustainable Development Goal 4 Quality Education

To achieve inclusive and equitable quality education and promote lifelong learning opportunities for all. The equal education of all groups and minorities within society is a necessary right, to ensure access to free schooling by 2030 and to provide equal access to affordable vocational training and to eliminate gender and wealth disparities with the aim of achieving universal access to quality higher education.

UN Sustainable Development Goal 5 Gender Equality

To achieve Gender equality and empower all women and girls. The equal representation of women and girls within society is a necessary right; goal 5 aims to end discrimination and violence against women in all public and private spheres. It also makes a call for women to be able to fully participate in all levels of society and have equal opportunities to take on leadership roles across all political and economic spheres.

Finding ways to create inclusive and equitable quality glass education and studios regardless of gender, race or an individual's societal demographic is still an issue many countries face. Examples of good practice, however, do exist and could be used as a model for the future. The Kitengela Glass Studio, based in Nairobi, Kenya, in collaboration with researcher Julie Ross, ran a series of funded workshops for local women from Kibera in 2018. The workshops introduced transferable art glass skills such as glass mosaic and bead making, to empower local women through glass making. Transglass, based in Guatemala City, in Central America, was originally set up by Emma Woffenden and Tord Boontje in 2005. It is a micro-enterprise that creates recycled glass products made by young people who are taught the transferable skills of glass cutting and polishing. Both of these glass studios highlight the potential that glass has to provide a vital source of income to vulnerable, low-income communities by offering them a route that tackles poverty and unemployment through a micro-enterprise driven by glass making. There are also systemic issues to consider, in caste system countries such as India, Bangladesh and Nepal where glass making is seen as a low status, male dominated profession. People are born into castes and carry out work that has always been carried out by their family. The caste system has had a major impact on glass making in these countries, however, it is changing and in busier urban areas non-caste glass workers are allowed to work in glass, whether or not this

Figure 9.6. Jessamy Kelly, Waste Glass Landscape, Recycled glass, Bombay Sapphire Gin Bottle (lost wax cast, kiln cast glass, diamond cut and finished), 2020, 18 x 8.5 x 48cm.
Source: Jessamy Kelly.

Figure 9.7. Maria Bang-Espersen, International Glass Prize in Lommel, Belgium (2012).
Source: Kristof Vrancken.

allows more equitable or inclusive access to glass is unclear.

Since the inception of the studio glass movement in the 1960s, glass education has spread widely throughout Europe, the United Kingdom, North and South America, the Antipodes and Asia. However, is Art Glass education accessible to all? Many European Higher Education Institutions offer reasonable fees or free education to resident students, however, international fees charged to study glass can be extremely high. It is this factor that has always restricted and inhibited access to those who wish to study glass, which has resulted in a lack of diversity and inclusivity. In the UK, widening participation schemes are in action, campaigns such as the Crafts Council *Make Your Future* [2] recognises that craft education in the UK is in crisis. The project has made considerable contributions to the field since its launch in 2014.

The recent Crafts Council England 2021 report, *Making Changes in Craft* [3], laid bare a review of racism and inequality within the UK Craft sector. The key findings in the report revealed the narrowness of the craft canon, the lack of alternative histories and narratives in craft; an urgent need to de-colonise the craft curriculum and the lack of initiatives to nurture Black and ethnically diverse makers. Examples of Racism and micro-aggression in craft spaces were also evidenced in the report findings. Finally, the perception of craft as a career was an issue. Many were discouraged from a career in craft by their families who viewed it as low paid, unstable work. Problems with the curriculum were also highlighted, with many courses dominated by a white, Eurocentric history. The report is an important move in the Crafts; how the Art Glass responds to this will be an important challenge to the field.

Hot glass workshops and factories have historically been a prime space for gender inequality, with men often dominating the field of blown glass in particular. In past decades, many renowned international educational centres for glass making have profited from essentially male only displays of macho, technical prowess in front of large audiences, often side-lining female counterparts. In the last decade, things have started to change with many glass artists challenging the *status quo* and taking their work to new professional and often performative levels. Glass artists such as Danish artist Maria Bang-Espersen have refreshed the field with their astounding technical and experimental displays in glass. She actively challenges restrictive norms and established hierarchies through her work (Figure 9.7). Other artists that are actively challenging the *status quo* are El Cocal Glass Studio, a collective of all young women glassblowers based in Murano, Venice, a place renowned for its male dominated environment. They call themselves the Vetraie Ribelli, 'Rebel Glassmakers'. The premise of their studio is simple— to eradicate a common prejudice that the profession of a glassblower is not suitable for women.

The recent winner of 'Blown Away', a glass blowing competition aired by the online streaming service Netflix, is also a timely example. Deborah Czeresko, a feminist glass artist won the show in 2019 with her inclusive approach, through her sharp social commentary wowing audiences with her free blown glasswork, which combines traditional Venetian techniques mixed with her own social commentary on contemporary feminist issues. Czeresko's 'Man-Bun in the Oven' project, created an external womb for men to wear to gestate and her feminist take on breakfast, which included a fecund fried egg and a chandelier of sausage links. Czeresko is a role model to many within the LCBTQI+ community and is keen to elevate the role of women in the field. She is well aware of the decades of patriarchy that has freely flown through the studio glass movement, stating: "While there are more women coming into the glass world now than ever before, it's important to keep this momentum going and for women to begin occupying a space that's been historically very macho" (Czeresko, 2019) [4].

Unique narratives and social commentary by women for women, that speak out about feminist issues through the medium of art glass is an exciting juncture for the Art Glass world. What is needed within the field is a wider range of voices, as teachers, mentors and role models to inform and lead the future generations of the international art glass movement. In reviewing the field of Art Glass, we still have a long way to go in terms of gender equity and diversity with many artists still discriminated against, under-represented and under-valued. Exhibitions, conferences and workshops are vital in raising awareness of the professional, high-level calibre of glass artists who are out there, possibly undiscovered. Finding new ways to represent them is a vital way to give their workspace to be seen and their voices heard. Exhibitions such as 'Unbreakable: Women in Glass' in Venice (2020) presented by Berengo Studio, which displayed a range of contemporary female artists working in glass. We should treasure spaces in which female artists are able to take centre stage… Many people in the art world would like to believe that we have achieved parity but the truth is we still have a long way to go. This is why spaces celebrating female artists remain so essential (Sterling, Fondazione

Figure 9.8. Choi Keeryong, 'Dam-Dah', kiln formed glass, 23.5ct gold leaf 2019.
Source: Choi Keeryong.

Berengo Art Space, accessed online 31.08.20).

The 'New Glass Now' exhibition held in 2019 at the Corning Museum of Glass featured a wide range of female and intersectional artists, of the 100 selected artefacts 59 were by women. Notably, within this exhibition was a project by glass artists and educators Karen Donnellan and Suzanne Peck. In their 2017 lecture, "Blow Harder: Language, Gender and Sexuality in the

Glass Blowing Studio” delivered at the Glass Art Society Conference in Norfolk, Virginia, they studied the vocabulary of the hot shop and proposed an alternative lexicon of terms that question the power dynamics, safety and inclusivity of glassblowing. Another notable work included in this exhibition is that of South Korean glass artist Choi Keeryong, whose work deals with otherness —the quality or state of being other or different. He debates the subject of cultural expectations through his work (Figure 9.8) and is inspired by his personal experience of being in a state of cultural in-between-ness, in terms of his current cultural location (Scotland) and his cultural origin (South Korea).

In 2020, North Lands Creative launched their online campaign —*Glass Lives Week*, with a range of films, podcasts, interviews and exhibition that showcased the diversity of the field [5] and celebrated a wide intersection of UK and European glass artists. This included Christopher Day, a glass artist of mixed English and Jamaican heritage. His recent solo exhibition at Vessel Gallery London ‘Blown, bound and Bold’ (2020) powerfully explored the treatment of black people in the UK and USA. His work references the 18th century slave trade and the social upheaval and events leading up to the American civil rights movement. In a recent podcast he was able to talk about how he became empowered through glass education, during his time at the University of Wolverhampton [6]. Also of note, is the work of Edinburgh-based, American Glass artist Jeff Zimmer who came second in the European Glass in Context (2021) Exhibition at the Bornholm Art Museum, Denmark with his glass work the “Shadow/Shelter”, an exploration of the lives of LGBTQ+ people in and from Caithness, a place in the extreme north of Scotland (Figure 9.9).

In summary, by defining the far-reaching effects of the international Art Glass movement, it is hoped that this text has offered an engaging and exciting space for us to celebrate the contribution that Art Glass brings to the UN Sustainable Development Goals. We should also take reassurance in an advanced community of glass artists,

Figure 9.9. Jeff Zimmer, ‘To Love You in Shadow’, kiln formed glass, 29.5 x 51cm.
Source: Shannon Tofts.

educators, curators, writers, collectors and enthusiasts who are finding new ways to express, represent, connect and make diverse voices heard. As well as the opportunity to introduce the powerful narrative of Art Glass to a new audience through the distinct social, political and environmental commentary of the discipline.

References

[1] https://www.glassart.org/programs/exhibitions/virtual-2021-green-exhibition

[2] https://www.craftscouncil.org.uk/learning/education/make-your-future

[3] https://www.craftscouncil.org.uk/documents/1512/Making_Changes_in_Craft_-_Craft_Expertise_Phase_One_Report_2021.pdf

[4] https://www.theartnewspaper.com/2019/10/04/glass-artist-deborah-czeresko-wants-to-elevate-the-role-of-women-in-the-field

[5] https://northlandscreative.co.uk/event/glass-lives-week/

[6] https://podcasts.apple.com/gb/podcast/chris-day-on-glassblowing-the-black-experience-and/id1450375359?i=1000533981567

TERESA MEDICI

10. Museums and Society

The most frequent figures given to estimate the number of museums in the world indicate that there are some 50 to 60,000 institutions worldwide [1].

CULTURE in all its expressions is an essential element in improving and developing the life and the well-being of people. Among cultural institutions, museums play a strategic role in making cities and communities inclusive, safe, and sustainable.

Museums are places where tangible and intangible heritage of humanity and its environment is preserved, studied, exhibited, and communicated for the purposes of education, study and enjoyment [2]. Receiving the name from the *Museion*, "the seat of the Muses", a cultural institute active during the third century BCE in Alexandria (Egypt), modern museums were mainly created to preserve and exhibit heritage, generate cultural awareness, and promote education.

Over time, their goal has become more complex to also include training and lifelong learning, and there is growing evidence that they can contribute positively to social cohesion and integration, civic engagement, health and well-being. Supporting the architectural and social development of cities and rural areas, museums can sustain the societies to face changes. They can stimulate creativity, increase cultural diversity, regenerate the local economy, attract visitors, and generate incomes.

Even if the origin of museums is rooted in western society and culture, most communities worldwide host museums and recognize them as a tool for empowering people by providing resources for learning and developing skills, enhancing the quality of life, and offering space for sharing ideas in a safe, inclusive and accessible environment.

Glass and the museum

Being not-for-profit multidisciplinary institutions open to people and embedded in the community, museums can play a strategic role in enhancing the knowledge of glass among citizens.

At the beginning of its production, more than 3500 years ago, glass was a valuable and treasured commodity, for the use of pharaohs and kings (Figure 10.1). Over the centuries, technological developments such as the discovery of glass blowing, combined with its invaluable properties (chemical inertness, impermeability, transparency), turned glass into one of the most exploited and versatile materials created by humankind (Figures 10.2, 10.3, 10.4).

Glass museums contribute to the preservation of glass heritage by means of acquisition, conservation, and protection of glass objects that people and communities recognize as deserving consideration and enhancement for present and future generations.

Not only dedicated organizations, but a number of institutions host glass collections of different origins and

Figure 10.1. Two-handled cosmetic jar with wide neck, core-formed. The body and the handles are of opaque dark-blue glass, the chevron decorations are in opaque white, yellow, and turquoise-blue glass. Height: 8.70 cm. Egypt, 18th Dynasty, ca 1390 BC-ca 1352 BC.
Source: *British Museum*, museum number EA4741.

Figure 10.2. Seven Roman Vessels (1st century CE). Blown. Blue-green glass.
Source: CMoG 77.1.2 A-G. Image licensed by *The Corning Museum of Glass*, Corning, NY (www.cmog.org) under CC BY-NC-SA 4.0.

Figure 10.3. *Murano Glass Museum.* Diamond-point engraved and filigree glasses.
Source: © Fondazione Musei Civici di Venezia - *Museo del Vetro di Murano* - Archivio Fotografico.

gathered for a variety of purposes. In the form of tableware, drinking glass, containers, windowpanes, personal ornaments, optical instruments, works of art, or scientific devices glass objects are spread in every kind of museum.

A variety of factors contributed to the birth of glass museums and collections.

The *Glass Cabinet* at the Rosemborg Castle in Copenhagen (DK), installed in 1714 and regarded as the first glass museum in the world, originated from a collection of precious Venetian glass gifted to the King of Denmark in 1709.

Exquisite glass vessels are exhibited in museums of decorative arts, originally created with the intention to improve the quality of national craft and industry by providing and showing selected

Figure 10.4. A. Palazzo Madama, Turin. Glass gallery. Islamic glass.
Source: Paloma Pastor - ICOM Glass. © Fondazione Torino Musei.

Figure 10.5. Covered goblet with cut decoration. Clear, colourless glass, blown, cut and wheel-engraved and gilt. Including lid height: 23.50 cm. Silesia or Bohemia, about 1760.

Source: *Victoria and Albert Museum*, accession number 6903&A-1860 © Victoria and Albert Museum, London.

samples of outstanding productions; good examples of this are the *Victoria and Albert Museum* in London (UK) or the Metropolitan Museum of Art in New York (US) (Figure 10.5).

Museums of science and technology have sections devoted to the display of scientific glass instruments that can date back to the 17th century, as the ones hosted by the *Museo Galileo* in Florence (I), or explaining the glass making process, as the *Musée des arts et métiers* in Paris (F) or the *Deutsches Museum* in Münich (D) (Figure 10.6).

The ancient history of glass can be traced in archaeological museums. Finds coming from archaeological excavations open a window on the use and trade of glass objects in the past. The Bronze Age glass ingots preserved in the *Museum for Underwater Archaeology* in Bodrum (TR) are evidence that the trade of glass as a raw material started very early in the history of its production: of Egyptian origin, they were found on a ship that sank off the Turkish coast, possibly on their way to the Mycenean world to be reworked.

In recent times, contemporary glass art is taking up considerable space in museum's glass galleries. By promoting national and internationals competitions and prizes, many museums contribute to the development of the artistic production considering glass as a favorite medium, encouraging and rewarding young artists for excellence. At the *European Museum of Modern Glass* in Rödental (D), the permanent exhibition includes several of the works submitted in the past for the Coburg Glass Prize contests.

To hand down the collections to future generations, conservation is a main responsibility for any museum. The work performed and the experience acquired on preservation and restoration of glass objects greatly contribute to our understanding of the materials used and of the mechanisms behind their deterioration. The results of the scientific investigation on glass supported by museums have revealed to be crucial for the correct interpretation of the collections, producing reference literature for the whole community of glass scholars. In museums laboratories curators and researchers can work alongside conservators and scientists, enhancing the common understanding of glass as a material, and producing state-of-art investigation. The research and conservation areas at *The Corning Museum of Glass* (Corning NY, US) pioneered the field and focused on the role of a specialized glass museum in sharing knowledge and best practices, acting as a medium between scholars, museums professionals, and the wider public (Figure 10.7). Robert H. Brill (1929-2021), one of the founding fathers of glass archaeometry, served as the museum's research scientist for more than 50 years. Important projects concerning the archaeometry of glass

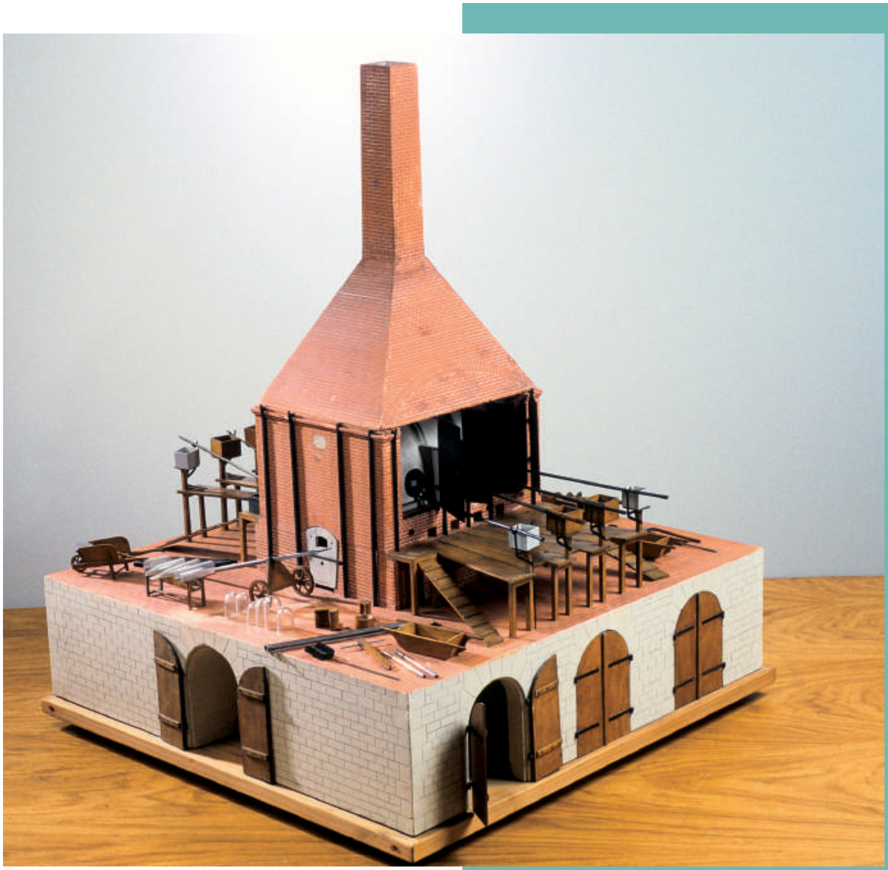


Figure 10.6. Model of a glass house producing cylinder glass by Appert, Mazurier & Cie, from the 1855 Paris Universal Exhibition.

Source: Inv 06439. Fichier 0003280_001© *Musée des arts et métiers*, Paris / Photo Studio Cnam.

Figure 10.7. Conservators Stephen Koob and Astrid van Giffen at The Corning Museum of Glass's conservation laboratory.

Source: Courtesy of *The Corning Museum of Glass*, Corning, NY. © Greg Hodges.

were developed in laboratories specifically created for the conservation and study of the cultural heritage preserved by museums, such as the *C2RMF - Centre de recherche et de restauration des musées de France*, whose facilities are located at the *Musée du Louvre*, Paris (F).

Museum's libraries and archives are invaluable resources for making research on glass and glassmaking accessible to scholars and the public. Keeping a record of the museum's activities and gathering specialized collections of books and documents, they strongly support the wider research community, an important example being the *Juliette K. and Leonard S. Rakow Research Library* of *The Corning Museum of Glass,* the world's leading institution on the subject. A valuable collection of glass auction and commercial catalogues, the oldest dating from 1744, is hosted by the library of the *Musée des Arts Décoratifs* in Paris (F).

Glass museums and the cultural landscape

Several glass museums have been created in regions or even towns traditionally devoted to glass production as for example the *Museo del Vetro* in Murano, Venice (I) (Figure 10.8) or *The Corning Museum of Glass* in Corning (US) (Figure 10.9). The complex of buildings created in the second half of the 18th century to host the *Real Fábrica de Cristales de La Granja* at the Real Sitio de San Ildefonso (Segovia, ES) is today the home of the Fundación Centro Nacional del Vidrio (FCNV), incorporating the *Museo Tecnológico del Vidrio*.

In areas where glass manufacture has ended, museums can occupy a very special place.

The decline of the glass industry in regions with a strong tradition of glass work has contributed to the conversion of industrial history into museum exhibits and community-based museography. The musealization of

Figure 10.8. *Murano Glass Museum*. First floor, large central room.
Source: © Fondazione Musei Civici di Venezia - *Museo del Vetro di Murano* - Archivio Fotografico.

abandoned glass factories collaborates in improving the regeneration of deindustrialized areas. Museums can play an important part in the mourning process following the demise of local industry and they can become important resources for local development. The cultural strength of these contexts can have a great effect on people, positively influencing their sense of identity. By preserving the memory of a common past and exhibiting a shared heritage, production places converted into museums help the community to reorganize itself, on the base of new economic factors. The company Glaces et Verres Spéciaux du Nord de la France, specialized in coloured window glass and better known as "Glaces de Boussois" (F), ceased traditional production in 1979. Today, former workers proudly guide the visitors around the tiny local *Musée de la Mémoire Verrière*, showing them documents, tools, and models of the past production plants and letting them know about the work and the life of the community.

Museums opened in ancient furnaces or factories can exhibit the machinery, utensils, and collections almost without removing them from the original contexts and backgrounds, increasing visitors' awareness. The *Atelier-Musée du verre* at Trélon (F) is located inside a late 19th century glasshouse with two furnaces for production of bottles and perfume flasks that were in use until 1977.

Figure 10.9. Tiffany Studios Wall Case and Mosaic Column, 35 Centuries Galleries, *The Corning Museum of Glass*, Corning.

Source: Courtesy of *The Corning Museum of Glass*, NY.

Figure 10.10. *The Gernheim Glassworks* in Petershagen (D).

Source: Peter Hübbe/LWL (Industriemuseum *Westphalian State Museum of Industrial Heritage*, Dortmund.

Particularly iconic are museums installed in the interior of the imposing cone-shaped glasshouses that represented a landmark in glass production areas, as the *Gernheim Glassworks* in Petershagen (D), and the *Red House Glass Cone* at Dudley (UK) (Figure 10.10). The symbolic force of these cone towers is so strong that modern structures destinated to host glass museums all around the world were build reproducing the shape, using glass and steel instead of brick and stone. The *Museum of Glass* at Tacoma (WA, US) and the *GlazenHuis* at Lommel (BE) are good examples of this influence.

Glass has demonstrated the capacity to be a powerful tool for urban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regeneration even in the absence of historical glasshouses. An outstanding example is offered by the plan *Glass Art City*, promoted by the City of Toyama (JP). Choosing glassmaking as a new cultural asset for the community development, the city created a system of institutions aimed at supporting talented glass artists and at spreading knowledge about glass arts and crafts. The structure is composed of the *Toyama City Institute of Glass Art* (a public educational institution), *Toyama Glass Studios*, and the *Toyama Glass Art Museum*, opened in 2015 in a breath-taking building designed by renowned architect Kengo Kuma. Great care was taken to ensure the participation of the community to this new cultural process, facilitating the interaction between the artists and the citizens by means of workshops, educational activities and glass-working experiences. As a result, Toyama is today home to the largest glass art community in Japan and the new glass culture is part of the life of the city.

The glass museum and the public

Being places of learning with objects, museums are crucial for dissemination, education and hands-on experience focused on glass. In every type of museum glass can be used as a medium to attract and actively engage the public.

Art, science, archaeology, history and social sciences find their meeting point in specialized glass museums and museums with collections of glass. Research carried out in museums fosters a deeper understanding of the tangible and intangible values of glass and glass objects, and the gained knowledge provides a sound basis for educational activities and communication.

Museums have plenty of stories to tell, describing raw materials and techniques needed for producing glass and glass objects through the centuries, teaching us about its origin and manufacture, and giving insight into the life of the people who created and used it. In the museum context, even the most common glass objects can provide unique learning experiences. Educational programs are designed to extend the understanding and knowledge in children and adults deepening the meaning of glass in their life. By establishing a creative relationship with schools, museums can contribute to the introduction of glass in formal and non-formal education, ensuring and promoting inclusive and equitable lifelong learning (Figure 10.11).

By sourcing and exhibiting objects and furniture with the aim of reconstructing the original aspect of the interior, historical house museums engage the public in glass collections in a particular way. Giving the visitors a sense of what the building's life was like when it was inhabited house museums stimulate active participation and a personal approach to the display.

Glass museums equipped with hot and cold workshops and studios can provide magical experiences for visitors and significant opportunities for creative learning (Figure 10.12).

The involvement of museums in glass production contributed in some cases to the reinvention and regeneration of an almost lost craft. In order to open a workshop where a visitor could observe the production of replicas of ancient glasses the *Museum of Ancient Glass* in Zadar (HR) gathered the knowledge of the last glassblowers in the country and succeeded in training young glassmakers. They are currently running a studio offering a varied and balanced set of glass making experiences.

Initiatives taken by museums have proved to be crucial in recognizing handcrafted glass production as Intangible Cultural Heritage. The manual production of glass is today recorded in the National Inventories of Intangible Cultural Heritage in countries like Finland, Germany or Spain. In 2020 "The art of glass beads in France and Italy" was inscribed on the UNESCO Representative List of the Intangible Cultural Heritage of Humanity, while a multinational application coordinated by France and involving also Germany, Finland,

Figure 10.11. Educational activities at the *Museo Tecnológico del Vidrio*, Fundación Centro Nacional del Vidrio (Segovia, Spain).
Source: © Courtesy of Fundación Centro Nacional del Vidrio.

Figure 10.12. Glassblower Korbinian Stöckle at work in the hot shop at *The Gernheim Glassworks* in Petershagen (D).
Source: Peter Hübbe / LWL (Industriemuseum *Westphalian State Museum of Industrial Heritage*, Dortmund).

the Czech Republic, Hungary and Spain will be submitted in 2022 with the purpose of inscribing on the UNESCO's List the knowledge, craft techniques and skills of handmade glass production.

Glassmaking activities are also tools which create inclusivity, and, in many museums, special attention is paid to community programs. The project "Tallando reflejos de vida. Mujer, vidrio y memoria" (Carving Reflections of Life - Woman, Transparency and Glass), developed by the *Museo del Vidrio* in Bogotá (CO), aimed to provide

Figure 10.13. ICOM Glass Meeting 2016. *Museo di Antichità*, Turin. Roman glass gallery.
Source: Paloma Pastor - ICOM Glass.
©MiC - Musei Reali, *Museo di Antichità*.

learning and training to women in a situation of social vulnerability by reactivating the glass decorative process of wheel engraving, a traditionally feminine craft.

Finally, without glass it would be impossible for museums to operate properly: thanks to technological advancements, all-glass display cases and large sheets of plate glass give museums the possibility of improving significantly the design of their exhibitions. In all of them, the essential glass is intended to be unseen.

Glass and ICOM

ICOM, the International Council of Museums, is a non-governmental organisation dedicated to museums and museum professionals. Founded in 1946, ICOM shared the vision of seeing in culture and education a reaction to a world war marked by extreme violence and brutality. In this vision, museums are identified as powerful tools, capable of strengthening bonds among people promoting cultural heritage worldwide and supporting citizens in building peaceful communities.

The specificity of glass in museums was soon acknowledged. Following the recommendations made by specialists of museums and collections of glass attending the 5th General Conference of ICOM in Stockholm (SE), on the 8th of July of 1959 the 6th ICOM General Assembly resolved to create an *ICOM International Committee for Museums and Collections of Glassware*, known today as *ICOM Glass IC*. The founding idea was that glass museums and glass departments would greatly benefit from close cooperation from each other. In order to further such cooperation, an inventory of museums and public collections of glass was launched. Special attention was placed to the enhancement of a scientific approach in conservation and restoration of glass in collections.

After more than 60 years, this mandate is as relevant as ever. Recognized as an international established network of museum professionals leading with glass, ICOM Glass organizes Annual Meetings worldwide, including scientific programs and visits, fostering the sharing of knowledge, and providing collaborative opportunities among members (Figure 10.13). A specific Working Group devoted to Glass and Ceramics was created by ICOM-CC, the ICOM International Committee for conservation professionals, with the aim of promoting glass conservation and restoration, disseminating information and best practice.

Glass museums and the 21st century

Museums are facing today the challenge of remaining significant in a rapidly changing world. They are driven to perform the basic functions described above while creating a more responsible relationship with their audience and communities.

The promotion of diversity and inclusion as opposed to inequality, the defence of human rights, and the accomplishment of the 2030 UN Sustainable Development Goals are issues museums are expected to address in their policies and everyday practices, sharing the vision of a peaceful, equitable, safe and sustainable world.

Is there any specific value that glass museums and collections can identify as a key factor in the process of building their new role in the society? Because glass is a unique combination of history, symbolism, technology, science, art, and everyday life it could be argued that glass museums are well equipped for this task. Speaking of glass to people is a powerful tool to increase inclusion and participation. Announcing that we are living in the Glass Age, David L. Morse and Jeffrey W. Evenson motivated their believe in this way: "The first reason is the ubiquity of glass and its central role in our day-to-day lives. We interact with glass screens on our computers and smart phones, take pictures through glass lenses, transmit and receive information via glass fibers, protect materials in glass covers and containers, and incorporate decorative and functional glass elements into our homes" (Morse & Evenson, 2016).

Glass started to impact on the world many centuries ago, and it will continue to do so. Museums will continue telling its stories.

References

[1] *Report on the implementation of the UNESCO 2015 Recommendation on Museums & Collections*, UNESCO 2019. Available at the UNESCO Open Access Repository (http://www.unesco.org/open-access/terms-use-ccbysa-en).

[2] The current ICOM definition of museum – "*A museum is a non-profit, permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment for the purposes of education, study and enjoyment*" – is at the present (2022) under revision: www.icom.museum

Further reading

Alberti, S. J. M. M. (2005): "Objects and the Museum", *Isis*, 96: 559-571.

Hahn, T. (1991): "In love with glass", *Museum International*, 43 (4): 202-205.

ICOM (2019): *Museum International* ("The Museum Definition: The Backbone of Museums"), 71.

Jackson, C. M. & Nicholson, P. T. (2010): "The Provenance of Some Glass Ingots from the Uluburun Shipwreck", *Journal of Archaeological Science*, 37: 295-301.

Morse, D. L. & Evenson, J. W. (2016): "Welcome to the Glass Age", *International Journal of Applied Glass Science*, 1-4.

OECD-ICOM (2019): *Culture and local development: maximising the impact. A guide for local governments, communities and museums*.

Simmons, J. E. (2017): *History of Museums. Encyclopedia of Library and Information Sciences,* Taylor & Francis: 1812-1823.

UNESCO (2015): *Recommendation concerning the Protection and Promotion of Museums and Collections, their Diversity and their Role in Society*.

Von Kerssenbrock-Krosigk, D. (2021): "Glass Museums", in P. Richet (editor), *Encyclopedia of Glass Science. Technology, History, and Culture*, Wiley: 1441-1455.

Weil, S. E. (1997): "The Museum and the Public", *Museum Management and Curatorship*, 16 (3): 257-271.

Ana Candida M. Rodrigues and John Parker

11. Education! Education! Education!

History

Early glass makers guarded their know-how with considerable enthusiasm. Allegedly an early Roman recipe for making gold ruby glass was lost for many centuries because of the failure of an overcautious father on his deathbed to pass on the secrets to his son as he had in life intended to do. Inevitably history has a habit of repeating itself. Figure 11.1 is a ruby glass vase which was the basis of a similar but much later issue! Conversely there are reports of one of the Caesars executing a subject who had discovered how to thermally toughen glass, a process perceived as having the potential to render worthless all of the glassware in the palace treasury.

Of course, over time the approach to intellectual property became more civilized but still had the aim of keeping it in the family. For example, in the 13th century, glass making was moved from Venice to the Island of Murano partly to prevent fire in the big city but also to confine all glassmakers' families in the island, thus avoiding the spread of secrets of glass fabrication. A less confrontational approach was to offer a worthy foreman the hand of a daughter in marriage. In a local 18th century factory this created its own problems. On the death of the factory owner his wife received the estate and would allow no further factory development. She even added to her own will a codicil preventing her son-in-law from starting a new factory within 10 miles of the one she owned. A new factory, giving the foreman his own opportunity for product development, was finally built 10.3 miles away.

Figure 11.1. A Ruby glass drinking cup. It was used in the film 'Heart of Crystal' by the German Director Werner Herzog (1976) to create the saga of a 18th-century Bavarian town, which produced Ruby Glass. When the only man who knew the secret to the production dies, the city goes into a great depression. The film illustrates how glass fabrication has been held in secret in past centuries.

Source: Ana Candida Rodrigues, UFSCar/Federal University of São Carlos & CeRTEV.

Glass artefacts have also featured in education and discovery in the Middle Ages: older monks creating artistically elaborate (illuminated) copies of the bible needed lenses to complement their eyesight; alchemists needed elaborate glass equipment for experimentation; later gentleman scientists such as Newton and Faraday demanded lenses to create telescopes that could explore the solar system.

Education for those sufficiently privileged goes back millennia. Indeed, education and knowledge are intertwined, as are knowledge and privilege. As society has become more egalitarian, education has slowly extended to a universal audience particularly during recent centuries and has taken on a wider scope. Schools, technical colleges and so on, have begun offering education for all. As knowledge has expanded in the last few centuries so specialist disciplines such as geology, chemistry and physics have grown apace and allowed people to better understand technical subjects such as glass making.

Ownership of recipe books (and technology) created a veil of secrecy in the industry that limited progress.

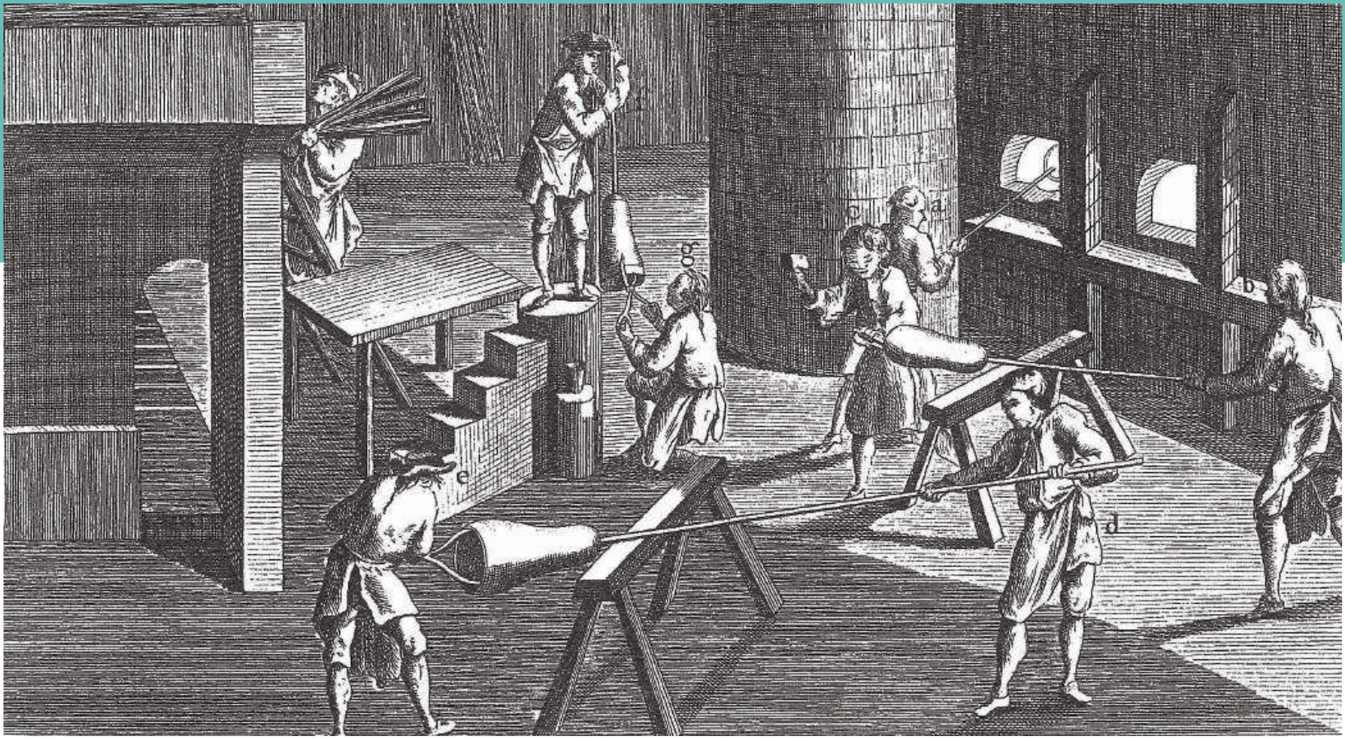


Figure 11.2. A glass furnace and glass blowers at work.
Source: Diderot and D'Alambert's *Encyclopedia* (Paris: Brisson, 1751-1765).

Nevertheless, many did record valuable insights. Among the earliest records are cuneiform tablets written by the Phoenicians; in the 9th century, Bede (a monk) and more recently Neri, Bontemps and many others wrote often from personal experience. In the 18th century, the Diderot *Encyclopedia* published plates illustrating aspects of glass making (Figure 11.2).

Otto Schott, in Jena, Germany in the 19th century recorded not just glass recipes but also were developing a systematic approach to the relationship between glass composition and property trends, no doubt building on the simultaneous developments taking place in chemistry.

Later, at the turn of the 20th century when universal education was growing rapidly, visionaries such as Turner in the UK realized that many problems were common across the industry and were best solved by collaboration, not competition. His vision quickly extended beyond the borders of the country; he discovered like-minded people throughout the globe (in Germany, Spain, Italy, France, USA and Russia), ultimately giving birth to the International Commission on Glass which included education and 'information' among its activities as well as research programs to develop understanding.

This was also a period of change and rapid development in the Glass Industry,

Figure 11.3. The value of recorded knowledge (textbooks) in learning.
Source: Pixabay.

from pots to continuous furnaces, from hand forming to machine operation, assisted by increasing skills and deeper understanding that empowered those responsible for the factories. Travel, although not a new phenomenon, also helped to broaden their minds particularly in terms of design. For example, members of the Wood family learned the latest hand-working techniques in France before returning to the UK to run a factory in Barnsley employing several thousand workers.

Industrialization and the move away from hand blown products in turn demanded different skills from the workforce: engineers to run the forming machines and the furnaces; lab technicians to monitor quality and so on. It spawned a major industry of suppliers to provide furnace refractories, forming equipment, control gear, capping and labelling equipment, secondary fabrication such as cutting, polishing, toughening etc. Education has had to change and develop accordingly.

Of course, hand-working skills did not disappear. After the first world war, there were many disabled soldiers seeking industries where they could work and make a contribution. Turner put on classes in Sheffield on lamp-working. The skills developed were taken up by the electronics industry and ultimately underpinned the development of radio, television, communications and computing.

Hand-working continues to offer valuable employment in artistic glassware. The Ruskin Mill based near Stourbridge, UK is a good example. Many with learning issues that make it difficult for them to fit into more conventional employment have discovered new opportunities. Home working is also once again a possibility and offers opportunities such as jewelry making and upcycling.

Current status

So, what constitutes effective Education? The dictionary definition of *Education* is: the act of imparting knowledge or skill; systematic instruction. So, there are (at least) two aspects of education, one is passing on skills and the second is the imparting knowledge. In either case a systematic approach is assumed. It's also worth considering the dictionary definition of *Learning*. This is said to be the gaining of knowledge, comprehension, or mastery of a subject through experience or study. This definition is further complicated for glass makers by the wide variety of skills and of knowledge needed within the subject of Glass Science and Engineering/Glass Technology.

Educational opportunities

So, 'Glass' lends itself to a wide range of educational opportunities. Despite its importance in our daily lives, the glass sector is relatively small compared with huge sectors such as steel and pharmaceuticals, and is one which has evolved from a multitude of small family run businesses where often education was organized by fathers for their sons, be they factory owners or master glass blowers. The industry now consists of a relatively small number of large multinational companies. Some are at least partly able to support their own education programs and the people at the top have often had a business training rather than one based on engineering skills.

All areas of the glass industry require a skilled, committed and educated workforce. Employees do need a basic appreciation of the material they are dealing with, to understand, for example, the importance of the optimum flame and batch pile distributions, the consequences of changing furnace loads, raw material characteristics, the factors affecting color, the sources and significance of seed, how the forming machines work, why fuel-to-air ratios are important and temperature measurements matter.

Figure 11.4. Teaching material is being developed on subjects such as glass and recycling.
Source: Pixabay.

Larger glass companies have often created a formal relationship with a local college of education and together developed appropriate courses to maintain a stream of suitably experienced employees. These often include apprenticeship schemes which may receive government support. Pooling of resources across different disciplines within the college can also help ensure viability. In many countries apprenticeships provide an accredited and well structured, more practical environment to formalize the educational process for younger entrants.

Of course, for such schemes to attract sufficient applicants, students must be made aware of 'glass' early in their education. In the UK, links are being created and teaching material developed on subjects such as glass and recycling (Figure 11.4). The International Year of Glass is an opportunity to stimulate such changes and to increase the awareness of the ubiquitous presence of glass in our daily lives. In Brazil the creation of comics based on exciting developments in glass is another approach. The International Commission on Glass has used the web to make them more widely available. Only through such actions will the best students join the industry. Indeed, as the glass industry has an age distribution which is typically top heavy, such training has a role in giving glass a future.

Another educational model designed around upskilling existing employees is the one day/one week course, both on- and off-line, often available from central organizations with a commercial focus and some companies are large enough to arrange their own programs. Similar teaching can be built into the national and international conference structure. It offers opportunities for building understanding through discussion and networking. Organizations such as Celsian (Netherlands) will also travel to give targeted instruction. This model avoids the extended loss of an employee from his normal duties.

For a part of the last century when change was particularly rapid and knowledge was expanding exponentially there were undergraduate courses dedicated almost exclusively to Glass, for example in Sheffield (Department of Glass Technology, University of Sheffield, UK) and Jena (Otto-Schott-Institut für Glaschemie, Jena, Germany). They were though exceptions. Targeted education to create the 'Works Glass Technologist' has now effectively disappeared at the degree level and the subject has been subsumed within the Materials Sciences.

Shorter, specialized postgraduate courses, such as one-year masters degrees can complement specific training in another engineering discipline by adding a detailed appreciation of glass making.

Research degrees and sponsored research programs are also needed to develop the subject, create new applications and specifically to help achieve the humanitarian goals listed elsewhere in this volume.

Recently the Glass Manufacturers Association in the USA has developed through widespread discussion an optimized syllabus for such educational models. In Australia too those involved in the flat glass processing industry have created an extensive set of online programs for workers in that field. In Brazil, in collaboration with a glass research group, a governmental institution recently created a training course to prepare technicians to work in glass plants and associated manufacturing areas. This initiative has been particularly successful, and the course has already its third cohort.

Ensuring a future

The discovery of the breakthrough process of float-glass, was based on a simple concept but involved many different steps to bring it to fruition. Since then, there have been numerous other developments in glass production, for example: in measurement and control, energy sources and efficiency, coating techniques, and specialist products such as bioglasses and mobile phone covers. All have needed people of education and imagination.

Many of the issues in running a glass furnace or processing glass have become the domain of the relevant experts within the supply chain. It remains the case that those in more responsible positions in the glass industry need a broad knowledge of many engineering disciplines, an awareness of who to talk to, and an ability to filter the information received.

The future will undoubtedly bring fresh opportunities with new markets and enhanced products. It will also come with its share of difficulties, starting with the need to ensure sustainability and a zero carbon lifestyle. People of insight, determination and energy are needed, able to access the huge databases of stored knowledge, imagine undreamt of solutions, anticipate hurdles and ensure glass takes its rightful place in our lives.

Wider aspects of education

Educating consumers on sustainable lifestyles depends on distributing information through standards, labelling and advertising. The concept of a "circular economy" needs to be fully comprehended so all can commit to the challenges of global change; ways to maintain a lifestyle without damaging the planet need explaining. Many organizations already do this and the IYoG2022 offers a unique and exceptional opportunity to disseminate best practices and the importance of a sustainable lifestyle.

While important in maintaining the *status quo* glass has shown a remarkable capacity to re-invent itself and help solve new problems that the world is facing be they medical, architectural, transport, communications etc. Much of this book is based around these themes. Individual enthusiasts are always needed to cope with ever changing circumstances and to push forward change.

Such progress can only be based on a sound foundation, an accurate and reliable knowledge base. That brings us to the final aspect of Education and Learning: the importance of understanding at the deepest level, which has as its starting point a process of questioning and leads to an exploration of the future.

One part of this process is the creation of textbooks, databases and even libraries which record what is known on the subject. Academia has played a vital role

Figure 11.5. A reminder of the importance of lifelong learning.
Source: Pixabay.

Figure 11.6. Cover of the ICG book 'Teaching Glass Better'.

in developing such information sources and helping with translation into a wide range of languages. An important part of the validation of such information is a formal refereeing process. The internet and intelligent search engines allow the effective sharing of such information but can also be a way in which erroneous information becomes incorporated into the knowledge base.

Of course, the internet and textbooks offer written and much duplicated records of man's knowledge but are less effective at conveying skills, an important aspect of education. The skills of the glass blower are only passed on efficiently by demonstration and practical experience. Recordings on YouTube are a poor substitute for working with an expert. This is being recognized in advanced countries that are now keeping a record of skills that are at risk, for example the making of glass eyes is recognized as almost a lost art in the UK.

Education and professional societies

For the general public, a quality education is the foundation for sustainable development. An inclusive education can also equip local communities with the tools required to develop innovative solutions to the world's pressing problems. A well-rounded education provides insights into the way society has coped with change over many millennia. Institutions that promote educational opportunities, also conduct basic research, organize well attended conferences, and publish advances in both glass science and engineering in highly respected journals or as highly acclaimed textbooks. At the same time their educational activities will be formally monitored and accredited by mutual comparison and often with the assistance of unbiased Professional Societies.

Glass making is highly skilled and numerous establishments offer courses a) for glass artists, b) the technicians to run factories and c) the research workers who use the unique properties of different glasses to create new products for the many challenges civilization faces. While specific data summarizing their annual economic impact are not available, it is clear a) they are located throughout the world and b) they are vital for advancing the fields of glass science, engineering and art.

Many of these activities are nurtured and chronicled by the International Commission on Glass —now in its 89th year of operation. Within ICG, Technical Committee 23 has been specifically tasked with the mission of stimulating an understanding of glass and promoting interaction among experts in glass science and technology, art, history, and education. It has for example produced a database of

Figure 11.7. Group activities, giving everyone a voice, are an important part of the learning process and of developing new ideas.
Source: Pixabay.

textbooks and offers specialist teaching courses, often linked to conferences. Simply allowing those in education to ‘rub shoulders’ with each other and discuss issues also plays a vital role.

The consolidation of automated industry over the last century has reduced the numbers employed even though output has continued to rise. To help revitalize worldwide glass education in a shrinking but nevertheless vibrant jobs market, 20+ ICG Summer and Winter Schools have been held since 2009. The Montpellier Summer School reached its 11th edition in 2019 and audiences continue to grow; in 2018, to celebrate its first ten years, the volume ‘Teaching Glass Better’ was published (Figure 11.6). It summarizes the course contents and captures the historical development and philosophy of the schools, explaining the lessons learned and offering a framework for others to follow. The Wuhan ICG Winter School in China achieved its 5th anniversary in October 2019 and in the same year a new school, the NASSPM (North America Summer School on Photonic Materials) was held in Quebec with great success. India has hosted two similar events and plans another, probably in 2025. The overlapping of staff across the schools and even students has helped to propagate and stimulate best practices in teaching methods. The book *Teaching Glass Better* celebrated 10 years of ICG Summer Schools, summarizing content and capturing their historical development.

These Summer Schools for young research workers typically last a week. All have been based on similar principles, teaching key underlying subjects, which extend thinking beyond a typical undergraduate level, but then critically, encouraging a more interactive approach to build confidence in questioning conventional wisdom (Figure 11.7). Such exercises have also helped to break down the natural barriers that exist between pupils and their teachers and created many long-lasting friendships across national boundaries that have helped support people through the Ph.D studies (Figure 11.8). These schools have also been useful in passing on teaching skills among staff from different parts of the academic community. Such schools can also bring together people from very

Figure 11.8. Students enjoying some sun during a coffee break at a Montpellier Summer School.

different backgrounds (e.g. the arts and sciences); the sparks so created always stimulate new thinking.

In 2021, the Montpellier Tutorial was forced online and indeed followed the example of an earlier school in India (also 2021). Considerable experience was gained on how to do this effectively but ultimately a school with face-to-face contact was seen as the preferred option.

But students respond differently to a variety of teaching styles and education is needed at different levels. Lehigh University, USA, has created a collection of hands-on demonstrations for high schools and the public. Its original version is at: https://www.lehigh.edu/imi/scied/libraryglassedu.html

Webinars and MOOCs are ways of passing on information to a large group of students but lose much of the interactive aspect that is vital for true education. The possibilities for creating such an approach for the glass community is on the agenda of TC23.

The commitment of ICG to education and outreach is also highlighted by its Youth Outreach Committee, whose goal is to organize events and mentoring programs aimed at attracting and retaining the future talents of the glass world. The idea is to provide them with the tools and the network for a successful career, where they will impact on industry and on society by developing and improving sustainable manufacturing methods and expand the applications of glass.

Of course, spotting and encouraging future talent has always been the goal of those 'at the top' but often sons, and only rarely daughters were targeted. UN GOAL 5 states that gender equality is a fundamental human right, and a foundation for a peaceful, prosperous and sustainable world. Educating companies and institutions in managing diversity, making it an engine for innovation and creativity, is the best route to a brighter future. Gender matters. Women are half of the world and must become half the glass world including education.

Nurturing exceptional talent of any gender is an important part of ensuring the future of any subject or organization. Another role that ICG and others have taken on is the award of prizes to younger members whose work demonstrates an unusual level of talent and enthusiasm. Prizes are awarded at various levels from those just starting to older members who have shown continuing excellence over many years. Even lifetime achievements are rewarded. The art world also has its competitions that promote innovative approaches and excellent workmanship. All promote the glass world.

Education is not only important at the highest levels but also for primary and secondary students, and for young technicians. Active programs targeting such groups are taking place in for example Brazil and India. We hope that a Year of Glass will encourage the wider sharing of existing practice and the stimulation of new ideas. Education is the best way to reach and instruct younger generations, raising their awareness of sustainable development goals and how to achieve them, starting from small changes in everyday life. Multiple examples need to be incorporated at every level, from elementary schools to colleges and university, to demonstrate the potential of glass in different applications and as an essential material to face the challenges of climate change and a sustainable society.

Many other national and international organizations have similar aims. ICG is in contact with the British Glaziers and GlaaS, its equivalent in Australia. Another goal of the IYoG2022 will therefore be to encourage the sharing of aspirations and to expand the scope of courses available. This will include reviews of standards and how these are maintained and even improved, a sharing of educational experiences across different sections, and the setting up and publicizing of a database of the courses and educational material available internationally.

Summary

Smooth running of industry relies on a well-educated work force, with the

Figure 11.9. Education, sharing our knowledge, underpins the creation of a more equal society.
Source: Pixabay.

appropriate skills and knowledge, experienced in how to deal practically with the problems that arise and the imagination to cope with an ever-changing world. Such skills and knowledge are learned in part on the job but are also passed on to newcomers by 'elders' in the community, and all build on the firm foundation of an appropriately tailored education. Finally, developing and maintaining formal education, to better prepare qualified staff for the glass industry and to publicize the importance of glassy materials to the general public is vital.

Further reading

TAKADA, A. *et al.* (2019): *Teaching Glass Better*, International Commission on Glass.

https://www.celsian.nl/academy

https://www.cmog.org/article/glassmaking-diderot-encyclopedie

https://www.lehigh.edu/imi/scied/libraryglassedu.html

https://www.gpi.org/glass-education

https://www.pilkington.com/en/global/about/education

https://www.glass.org/resources/education-training

https://www.bullseyeglass.com/landing-page/education.html

ALICIA DURÁN

12. Gender Equality and Diversity in the Glass World

Half of the brainpower on Earth is in the heads of women. …Today, the difficulty is to move from the acceptance of equal rights to the reality of equal opportunity. This transition will not be complete until women and men have equal opportunities for occupying position in power structures throughout the world.

Donald J. Johnston, General Secretary OECD

FEMINIST economists and sociologists have developed two powerful metaphors to explain the employment situation of women. The *glass ceiling* explains the difficulty of many women to access the highest professional levels, the very low presence of women in positions of power and the lack of recognition of the work of many professional women.

The *sticky floor*, on the other hand, refers to the large numbers of women condemned to occupy the lowest ranks of the occupational pyramid: temporary, part-time, low-wage jobs, considered "unskilled", etc., a floor from which they cannot escape during their working lives and which is usually inherited from mothers to daughters [1].

The scientific world has historically mistreated women. Rosalind Franklin obtained the first X-ray image of DNA but Watson, Crick and Wilkins received the Nobel Prize. Jocelyn Bell discovered pulsars but her Ph.D thesis director was awarded with the Nobel Prize. And Marie Curie twice won the Nobel Prize, but only 3% of these prizes in medicine, physics or chemistry have been conceded to women.

Figure 12.1. Old postage stamp with portrait of Marie Curie, who is best known for her work discovering polonium and radium radioactive isotopes.

Source: 1967 French postage stamp commemorating the 100th anniversary of Marie Curie's birth, La Poste de France.

The historical discrimination against women in the world of science continues to be present. On March 8, 2021 there still was only one woman for every nine men in the elite of European science. European women scientists occupy very few decision-making positions; their jobs are often evaluated more harshly; they get less funding and fewer fellowships to investigate; and their salaries are lower than those of their male colleagues.

Science, as any social phenomenon, is not isolated from the historical and socioeconomic context, and its progress is closely related to power structures and relationships: economic, political and gender. There is a general philosophy according to which creative and original work that gives rise to radical transformations is produced by men, while women are more efficient in technical tasks, in obtaining data, in putting "order" in the laboratory. This idea reflects the androcentric character of scientific-technical systems, which assume that being a scientist means being part of a masculine profession and having to overcome the supposed "disadvantages" of the female sex [2].

The European Technology Assessment Network (ETAN) report, published in 2001 by the Helsinki Group, reviewed the position of women in science and technology in Europe, concluding that the "under-representation of women threatens the goals of science in achieving excellence, as well as being wasteful and unjust" [3].

A statistical review of the women in positions in higher education, research institutes and industry shows that, despite geographical variations in systems and structures, the proportion of women in senior scientific and CEO positions is extremely small everywhere, making visible the gender segregation within the scientific field. The number of women in scientific careers shows a downward curve, with a continuous drop from the beginning of studies, where they tend to be the majority, to the higher scales of full professor, where the proportion of men is always higher. This surprising snapshot is a constant all over Europe. This situation, known as the "*scissor graphic*", is described as a "*leaky pipeline*", where women disappear from scientific careers disproportionately and constantly, and many highly trained women are lost from science [4].

The gender imbalance in R&D institutes is similar to that of Universities. Moreover, in EU industry, the best rough estimate of the proportion of women in top positions is around 3%. In June 2019, just 33 of the Fortune 500 companies had a female CEO, 6.6%. To ignore these patterns is to accept discrimination in the sciences.

Businesses of all sizes have the same natural biases; a further phenomenon appearing in the discrimination of women is: the *glass cliff*. Frequently, when a company or institution is going through a period of crisis, women are appointed to leadership positions, when the risk of failure is highest. Extending the metaphor of the glass ceiling, the notion of the "glass cliff" refers to a danger that involves exposure to risk of falling.

A 2013 study by Alison Cook and Christy Glass [5] on CEO transitions in Fortune 500 companies over a 15-year period, found that the appointment of women CEOs traditionally followed poor company performance. To make matters worse, women CEOs are 45% more likely to be fired than their male counterparts. Who are these women CEOs replaced by? Typically, white men, a scenario dubbed "the savior effect".

Figure 12.2. Girls sharing lectures.
Source: Pixabay.

Why do so many high performing women accept positions that seem almost impossible to overcome? These positions although risky, provide the opportunity to have a big impact and change the course of a company. An excellent example is Iceland. After the banking crash, Iceland's women led the rescue, determined to reinvent business and society by injecting values of openness, fairness and social responsibility. From the Prime Minister to CEOs of the two biggest crashed banks, Iceland's experience shows that giving women an equal say in how business and society are run can change the world for the better.

Different reasons explain this discrimination. Out-dated practices characterize employment selection systems and promotion procedures in academic and industrial institutions. "*Old boys' networks*" and personal invitations to occupy posts hinder and obstruct fair and effective employment procedures. Both sexism and nepotism have been documented as interfering with the peer review process.

However, the causes of this phenomenon are more complex and do not come exclusively from male discrimination. There are also values deeply rooted in society, and of course in women themselves. The gender relations in scientific environments are still and often based on a lack of recognition from the masculine side of the intellectual capacities of women, this being used as a pretext to keep them in the margins of activity, without access to real decision sites.

The 1957 Treaty of Rome established the principle of equal treatment of men and women, and European national legislations from the 1970s and 1980s made sex discrimination illegal. However, in the twenty-first century, men and women are still segregated in sciences. This segregation is:

- Horizontal: women are clustered in certain areas of science (biology, medicine).
- Vertical: women usually constitute about half the undergraduates in many disciplines, but they are a small fraction of the professoriate.
- Contractual: men are more likely to get tenure, while women take more short-term and part-time contracts.

Key science figures described in ETAN show an extremely narrow social base in terms of age, gender and ethnic origin. White men over 50 overwhelmingly dominate senior scientific committees that award research funds, grants and prizes. The lack of women in strategic decision-making positions is not just a matter of equity and gender balance. This will inevitably affect the drawing of the scientific agenda and the decisions about investment in research areas.

The segregation and male dominance in science is far reaching and self-perpetuating, feeding back into media, education and social values cited above.

How to face the segregation, arguments for change

Following the UN Beijing Conference on women in 1995, the ETAN report highlighted the importance of "*mainstreaming*", or *integrating gender equality*, as a main policy to be implemented in science.

A subsequent report of the Directorate-General for Research of the EU [6] confirms that the under-representation of women on decision-making scientific boards implies that the individual and collective opinions of women are less likely to be listened to in policy and decision-making processes, affecting the drawing of the research agenda. Moreover, if women scientists are not visible, they cannot serve as role models to attract and retain young women in scientific professions.

The report evaluates the data, identifies existing problems and the arguments for change, and proposes actions for advancing the position of women in research, contributing to equality and quality. The arguments in favor of having more women in research decision-making positions are abundant, from human rights and ethics to economics.

Human rights arguments

The arguments of social justice and fairness say that men and women should have equal opportunities and suffer no discrimination. Moreover, improving fairness for women improves fairness for all.

Arguments concerning diversity, quality and efficiency

Diversity increases creativity. Research activities rely heavily on creativity. Diverse research teams from varied origins are in general more open to new ideas, procedures and experiments, and are thus more innovative. Research departments in multinational companies that actively develop programs to hire and retain women (as well as ethnic minorities) throughout their careers have long recognized this [7].

Diversity increases quality [8]. The more diverse the background and experiences of the researchers, the less likely it is that research is biased, or that products target only part of the market. The closer to reality the research is, the better it can produce products that people actually need and use.

Having gender balance in research brings science closer to society by reflecting its actual composition. Gender equality facilitates the inclusion of social needs and the targeting of areas otherwise easily neglected in the research agenda.

Gender equity improves efficiency. This agrees with a new orientation of universities towards business strategies. The economic world asks for more qualified personnel as 'human capital'; starting from a lack of qualified men, it turns to women and immigrants, considering the recruitment of highly qualified female researchers as a prime policy objective, particularly in male dominated fields like engineering, and even going beyond national borders.

Gender equity increases international competitiveness. Universities and research institutions with very few female professors could lose out in international competition against partners with greater participation of women researchers, thus counting on a larger pool of talent, and the benefits of increased quality brought about by greater diversity.

Benefits of mainstreaming diversity in business

Businesses are unlikely to change their corporate cultures because doing so is "nice" or "fair" for women. They may do it if there is a compelling business reason to do so. The bottom-line reasons to achieve gender diversity in leadership are indeed compelling. The business case for gender diversity and inclusion affects [9] [10]:

- *Returns.* Gender diversity in leadership is strongly correlated with higher returns, profitability and share price. Diverse groups (while harder to manage) simply perform better. Companies with a higher percentage of women in executive positions have a 34% higher total return to shareholders than those that do not. Companies with the most women directors outperform those with the least return on invested capital by 26%.
- MSCI Inc. studied the financial performance of U.S. companies from 2011-2016 and found that those with at least three women on the board had median gains in return on equity 11% higher, and earnings per share 45% higher, than companies with no women directors.
- Gallup studied 800 business units from the retail and hospitality industries in 2014. They found that gender-diverse business units had better financial outcomes, including revenue and net profit, than those dominated by one gender.
- The Credit Suisse Research Institute reported that companies with at least one woman on their board outperformed the peer group by 26% over the preceding six years.
- *Talent pipeline.* To have the most skilled and talented workforce, a business must attract and retain women as well as men. Engaging as much of your workforce as possible is good business; involved employees do more and better work and are less likely to leave.
- *Women's market.* Women represent a growing portion of the customers, clients and partners of many businesses, having huge buying power. Tapping this market is crucial to business growth.

Gender matters more and more, and significant changes are glimpsed in SciTech. Indeed, women in tech are committed to staying in the industry

Figure 12.3. Protest of women attendees to the PNCS congress in Saint-Malo 2018, demanding parity in the invited talks.

and encouraging the next generation to follow suit [11]. Women share this commitment across different stages of their careers, from early career professionals with 1-5 years' experience (80%), experienced professionals with 10+ years' experience (83%), and re-entrants to tech —women who have returned to the industry after taking a career break (88%). These figures indicate that satisfaction of women in tech improves as they progress in the industry and is positively influencing their intent to stay. Globally, nearly nine in ten women tech professionals (89%) say they would recommend a career in the tech industry to the next generation of high school and female undergraduate students.

Glass ceiling, sticky floor and glass cliff in the world of glass

Women in academia, researchers and technicians, suffer most of the mentioned problems; this leads to wage gaps including in public organizations such as universities and R&D centers. The Spanish Organic Law 3/2007, for the Effective Equality of Women and Men, established the obligation of designing an Equality Plan in all public bodies and companies. In public R&D institutions as CSIC, important progress has been achieved but important differences remain, such as:

Figure 12.4. Cover of IJAGS special issue Women in Glass.

Figure 12.5. The glass blower Olga García finishes a piece in the Real Fábrica de la Granja, Spain.
Source: FCNV, La Granja, Segovia, Spain.

- Higher rates of temporary employment in women in comparison with to men.
- Among research staff the scissor graph (glass ceiling), remains or has even worsened in the last 10 years.
- In technical staff, women are concentrated in the lower levels and are not promoted (sticky floor).
- Although salaries are fixed, wage discrimination (wage gap) occurs through the productivity system (extended working hours, supplements for higher responsibility, etc.) derived from a deficient personal/family and work balance.

Other forms of discrimination feature widely in congresses and conferences, where the numbers of invited talks and keynote lectures are always much lower for women compared to men. Indeed, a curious demonstration was organized at the PNCS conference in 2018 in Saint-Malo, when women attendees, close to half the total, represented less than 15% of invited talks. Figure12.3 shows their protest at the dinner. Something is moving in the glass world.

To improve the visibility of women it is worth citing the special issue on Women in Glass published by the International Journal of Applied Glass Science (IJAGS). The issue highlights a group of outstanding women researchers who are developing their careers in academia, government laboratories and industry in 12 different countries and across a wide range of topics related to glass (Figure 12.4).

Another interesting issue is that the job of glassblower, an eminent and nearly exclusively masculine profession, is becoming feminized and many women blowers are learning the trade (Figure 12.5). This impacted on a Spanish initiative to nominate glass-blowing as a Spanish cultural heritage, intending to preserve a centennial skill worthy of support and protection. Contacts are in progress with other nations to propose that UNESCO should nominate glass-blowing as a World Heritage of Humanity.

Figure 12.6. Gemma Martini (in black, second row), CEO of Vitrum Glass Group, based in British Columbia, with the all-women Insulating Glass Unit assembly team.
Source: Vitrum Glass Group.

The situation is also moving in glass companies. Although the women in CEO and Board positions of multinational glass companies are around 10%, women's networks are emerging to promote gender equality and diversity. Saint-Gobain, Schott and Corning are good examples with programs for managing diversity and gender equality. And many SME's workforces are becoming more and more feminine (Figure 12.6).

A common view focuses on the necessity to revamp the image of the glass industry as an employer interested in attracting and retaining the next generation of young leaders. As Dr. Diane Nicklas declares [12] "it is crucial to shape global and diverse teams; the key is the combination of 'technology' and 'people'. The Glass industry clearly lacks gender diversity and it's difficult to find many women in leadership functions. However, it is difficult to find many women in junior positions either, which means that the problem of diversity will continue to exist. We face the challenge of attracting an entire new generation. At first glance, no heavy industry nowadays is appealing to the young generation. We are neither exciting, nor techy, nor cool in their eyes. Their interests focus on the environment, sustainability, networking & culture, innovation, digitalization, high-end technology, and working for purpose-oriented organizations.

Women in a very natural way bring other skills to those found in a team composed exclusively of men. Diversity has proven to be an essential key success factor for teams and companies. Further benefits could reinforce the glass industry if an additional dimension of diversity were included, namely 'cultural diversity', even more important if the glass company serves customers at an international, if not global level.

As explained by Chiara Corazza [13], Science, Technology, Engineering and Mathematics (STEM) account for "70% of the most in-demand skills", but women account for only 24% of professionals working in STEM roles worldwide, only 35% of students and only 1 in 5 graduates across Europe.

CGénial Foundation, partnered by Saint-Gobain is working to implement some practical ideas that promote gender diversity and female leadership in STEM careers, including glass companies [14].

- *Promote inspirational careers for women*, breaking preconceptions by bringing students face-to-face with the scientific community. These out-of-school interactions allow girls to associate themselves with STEM opportunities by meeting role models and hearing about inspirational career journeys.
- *Set quotas and quantified targets for gender inclusivity in science and technology careers*: "a quantified target of 40% representation by girls in public and private sector STEM universities and graduate schools by 2025, backed by financial incentives conditional on progress towards this goal" is recommended. Another option is to impose a 40%

Figure 12.7. Education of girls is the key to improve diversity and gender equality.
Source: Pixabay.

membership quota for women on corporate executive and management committees.

- *Make the move from STEM to STEAM.* Recently a new acronym is emerging: STEAM. The addition of the letter A refers to Arts, and to the wider issues around not only creativity, but also social and societal commitment. Promoted by UNESCO, the STEAM method is an effective way of attracting women into scientific careers using an interdisciplinary approach.
- *Develop STEM networks for women.* WiT (Women in Tech), Réseaux Industrielles and WomenTech Network in the USA… In the corporate world, women are coming together and engaging in initiatives to raise awareness of issues around gender diversity in STEM careers with the goal of moving beyond preconceived ideas.
- *Raise teacher awareness of what STEM careers really are.* More and more engineering, IT and other major companies are hosting visits to production facilities and/or R&D departments to raise school awareness of corporate culture. These bridges between industry and schools encourage interaction and help deconstruct certain received wisdom about STEM careers, at the same time as highlighting the associated challenges, particularly in terms of recruitment and gender diversity.
- *Learn to code at an early age.* It's crucial to develop computer science and coding in schools. French projects as well as approaches in the UK and Canada promote collective intelligence and creativity in ways that exclude any suggestion of gender specificity.
- *Ensure gender diversity in AI development teams*. Algorithms are biased. The fact is that men write the vast majority of these lines of code that are increasingly structuring our world. Indeed, only 15% of all the data scientists in the world are women. It's a lack of diversity that is having serious consequences. Gender diversity in AI development is essential if we are to develop new gender-neutral technologies.

These new views on diversity aim to answer a key question: *Can a system that ignores half of the labor force be successful and economically efficient?*

To break the current situation, it is essential to change radically the governance bodies of companies, incorporating diversity as a key factor in employment policies. The role of team leaders is crucial; they must be able to create an atmosphere that encourages people to share different perspectives, guiding groups to consider different opinions and discussing them instead of simply opposing them [15].

Moreover, to go beyond the surface is essential. Encouraging companies to apply diversity does not merely mean hiring women and people from different countries! It means recruiting individuals with shared professional values whilst possibly having different perspectives. Promoting education in companies and platforms to learn how to manage diversity and make it an engine for innovation and creativity is the best way to build a brighter, more diverse future.

The necessary changes should focus on advancing [14]:

- *from inertia to awareness and commitment*: a sincere commitment is necessary, particularly among leaders in science and industry, with the goal of equality —for the benefit of quality,
- *from imbalance to balance*: a reasonable gender balance (e.g. 40:60) with suitable steps should be made mandatory in decision-making bodies,
- *from opacity to transparency*: transparent procedures should be implemented by the sci-tech community, and the criteria, success rates and evaluation reports must be made public,
- *from inequality to quality*: with measures to systematically introduce the gender perspective in human resource development and in

Figure 12.8. Woman working in a glass factory modelling hot glass.
Source: iStock / Getty Images Plus.

research programs. This includes training decision-makers and eradicating gender bias in research, recruitment and promotion procedures. There can be no quality without equality,

- *from complacency to urgency*: the glass world needs women and the young. We must act now.

A few but relevant conclusions

The limits to the participation of women in sci-tech are not professional limits, but social limits; limits that derive from a sexist educational model, which forces women who decide to work in science to identify themselves with models that pretend to be neutral but are definitely masculine [16].

In addition to implementing diversity and mainstreaming gender policies, the contradictions generated between quality and professional value on the one hand, and expectations and social images of women on the other must be overcome. This means betting on outputs where the logic of equality nurtures and supports the logic of difference, a commitment to building another science from women themselves, another way of approaching scientific work —already proposed by *Science or Nature*— which combines vital options and does not require a choice between professional and personal life.

Gender equality is a task that transcends the world of research and industry because it must begin with the transformation of education into a co-educational project, with teachings that transmit transformative knowledge, that recognize and incorporate the social relations of sex and constitute a stage towards a more complete culture, made by men and women. This is the challenge because this is the future.

References

[1] Durán, A. (2019): "Breaking the glass ceiling", chapter of the book published by Nippon Electric Glass for its 70th anniversary.

[2] Arditti, R. (1982): "Feminism and Science", *The Changing Experience of Women*, The Open University.

[3] European Commission (2000): *Science Policies in the European Union. Promoting Excellence through Mainstreaming Gender Equality*, ETAN Expert Working Group on Women and Science.

[4] Etzkowitz, H. *et al.* (1994): "The Paradox of Critical Mass for Women in Science", *Science*, 266: 51-54.

[5] Cook, A. & Glass, C. (2014): "Above the glass ceiling: When are women and racial/ethnic minorities promoted to CEO?", *Strategic Management Journal*, 35 (7): 1080-1089.

[6] European Research Area (2008): *Mapping the maze: Getting more women to the top in research*.

[7] European Commission (2006): *Women in Science and Technology. The Business Perspective*, EUR 22065 EN: 19-25.

[8] Barres, B. A. (2006): "Does Gender Matter?", *Nature*.

[9] Turner, C. (2017): *The Business Case for Gender Diversity*, Difference WORKS, LLC.

[10] Solomon, C. (2018): "Unlocking the Business Benefits of Gender Diversity", *Culture Wizard*.

[11] BOOKING.COM RESEARCH (2018): “More than Four in Five Women in Tech Globally Intend to Stay in the Industry, and Are Taking the Lead Towards Achieving Gender Parity”.

[12] https://www.glass-international.com/features/a-female-career-in-the-global-glass-industry

[13] CORAZZA, C. (2020): “Women at the heart of the economy”, Women’s Forum for the Economy & Society.

[14] https://www.saint-gobain.com/en/magazine/stories/7-practical-ideas-greater-gender-diversity-stem-careers

[15] AMELI, I. (2018): “How Diversity can be an Engine of Creativity and Innovation”, Twinkle Association, Communication and Marketing Professional Studying Master of Global and Transnational Sociology at University of Tampere.

[16] DURÁN, A. (2002): “¿Cambiar a las mujeres o cambiar la ciencia?”, *Arbor*.

LOTHAR WONDRACZEK

13. Glass beyond Glass

UNDERSTANDING glasses has always had its metaphorical aspects. Among the earliest efforts to capture the nature of glass, 9th century cleric Hrbanus Maurus [1] was fascinated by visual transparency, which enabled clarity of view but also, at the same time, solid confinement. In some sense, this reflects our present understanding, where we see glasses all around us, but yet, recognize only a small fraction of the full versatility offered by this particular state of matter. Furthermore, we still do not understand the fundamental process and constraints which lead to the formation of glasses from their liquid parent states; 25 years after Phillip W. Anderson's widely cited statement, *glasses remain one of the greatest problems in solid-state physics* (P. W. Anderson, 1996).

Universality of the glassy state

Beyond their material manifestations, optical or mechanical properties, glasses are sometimes understood as representing infinity: neither truly solid nor liquid, they are assumed to flow on infinite timescales; the dependence of glass (and liquid) viscosity on temperature is one of the strongest known to physicists. Spanning more than 25 orders of magnitude, it translates into relaxation times which range from the smallest fractions of a second to centuries, millennia and aeons.

Similarly, the other characteristic of the glassy state. Spatial disorder has occupied generations of scientists in their quest for correlations, tools and physical relationships which would help

Figure 13.1. The glassmakers art relies on the viscosity-temperature characteristics of glass.
Source: L. Wondraczek.

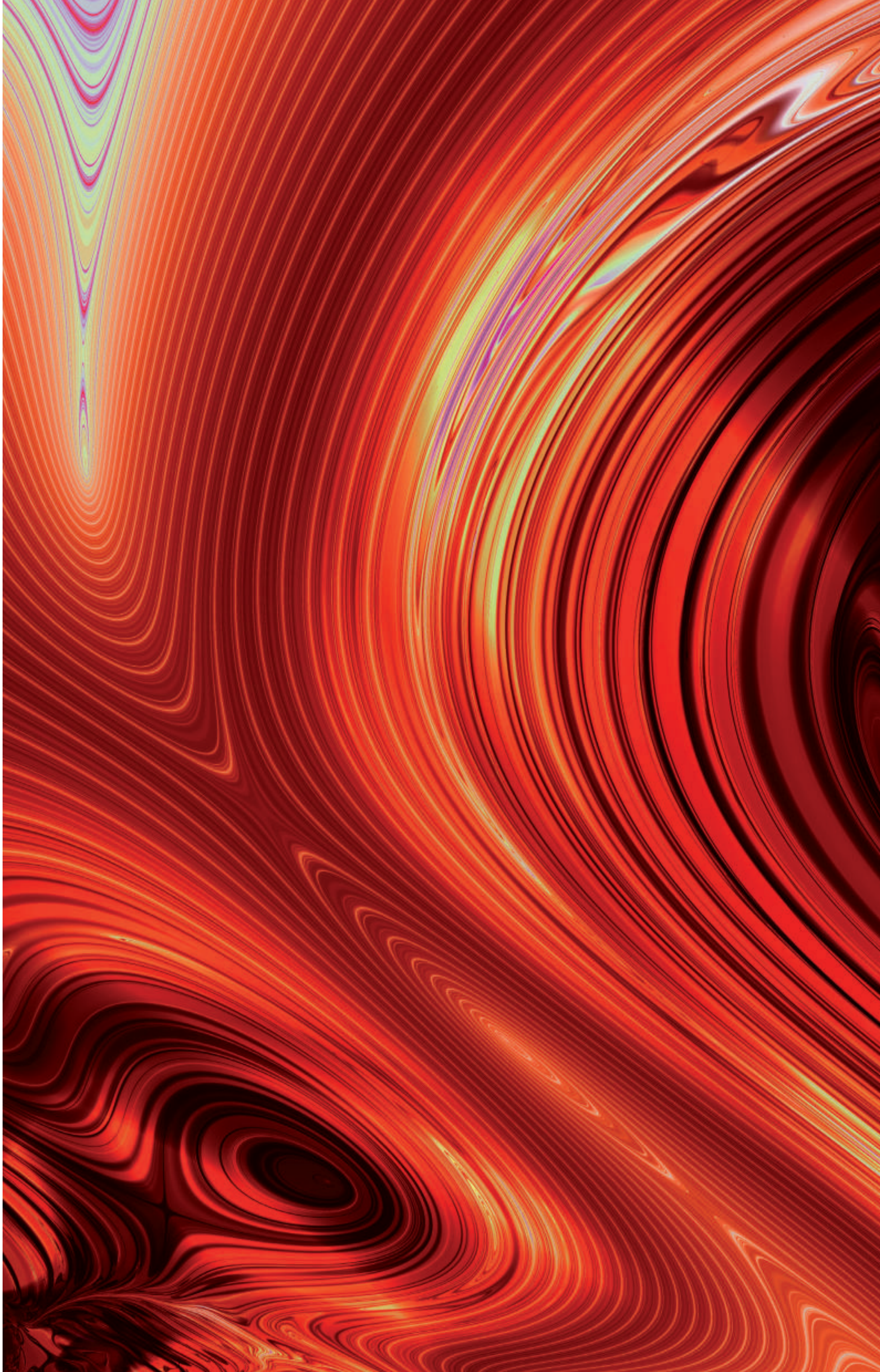
to understand the macroscopic properties of glasses. Where their ordered counterparts —crystals— offered lattice periodicity and, as a consequence, powerful theory for predicting real-world behaviour, similar tools have remained elusive in the glassy world. Disorder was often associated with randomness and chaotic dynamics. However, the sheer existence of chaos has remained disputed over ideas of infinitely complex cycles which determine the dynamics of complex networks [2]. Meanwhile, we have learnt much about the structure and dynamics of the glassy state so as to assume now the existence of order in disorder, a *glass genome* yet to be deciphered [3].

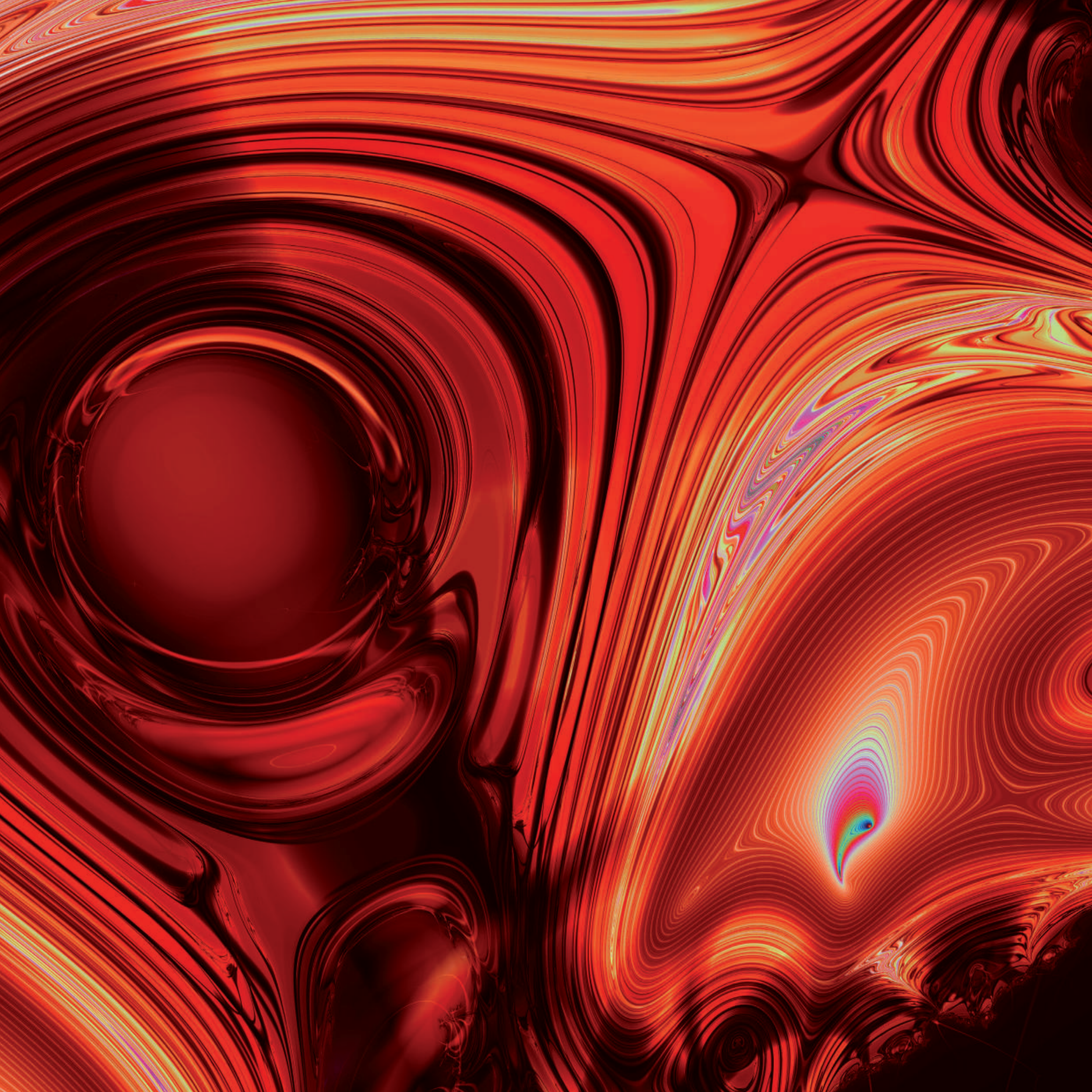
None of the physico-chemical definitions of the glassy state is restricted to any particular class of materials, chemical compositions or product property. Indeed, glasses exist across all classes of chemical compounds, from the classical silicate and mineral compositions to non-oxide and metallic materials, from inorganic to organic and hybrid compounds [4]. New classes of glass are frequently discovered, for example, in metal-organic frameworks, coordination polymers and, most recently, hybrid perovskite derivatives [5]. Beyond chemical considerations, researchers work with computer or physical models comprised of hard spheres or other objects with variable interaction terms replacing chemical bonds, spin glasses evolve from magnetic disorder, and many other manifestations of glassy disorder are being explored as examples for the dynamics of complex systems. Thereby, the glass itself often provides a snapshot of the liquid from which it was obtained: while a liquid is hard to observe, once its dynamics are frozen-in, a plethora of analytical tools becomes available and can give further insight on structure-property relationships.

A material driven by process technology

Returning to the transition from liquid to glass, it is precisely this characteristic that constitutes the practical interest and industrial importance of glasses and vitreous materials: the temperature dependence of the viscosity of glass-forming melts and their (super-cooled) liquids.

The most widespread route to create a glass is to cool down a liquid sufficiently rapidly, which leads to an increase in viscosity and, thus, a decrease in the mobility of the liquid's (atomic) constituents. This latter effect creates a kinetic barrier against assembling into





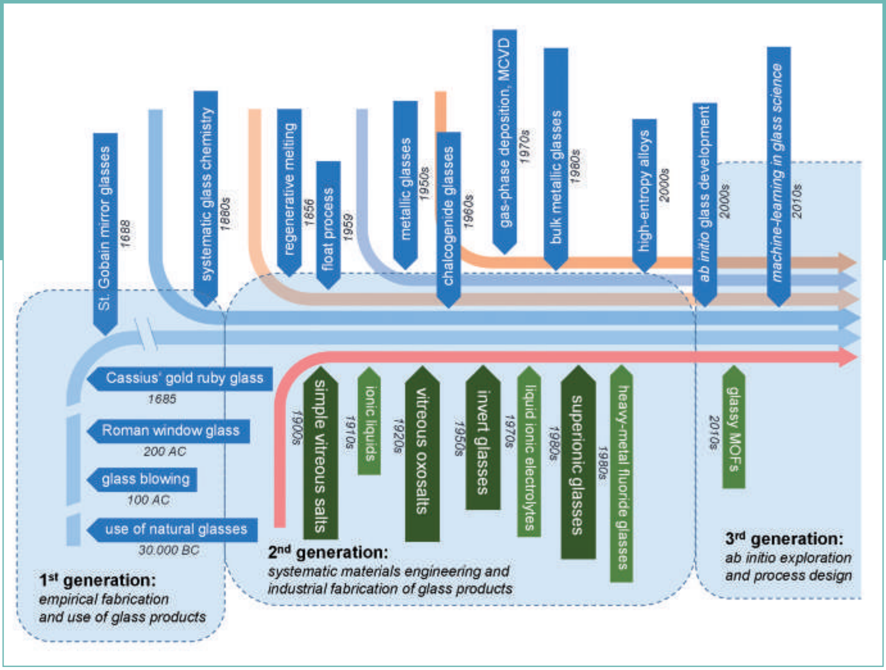


Figure 13.2. Glass milestones and the generations of glass technology.
Source: Adapted from Ref. [7] under CC-BY license.
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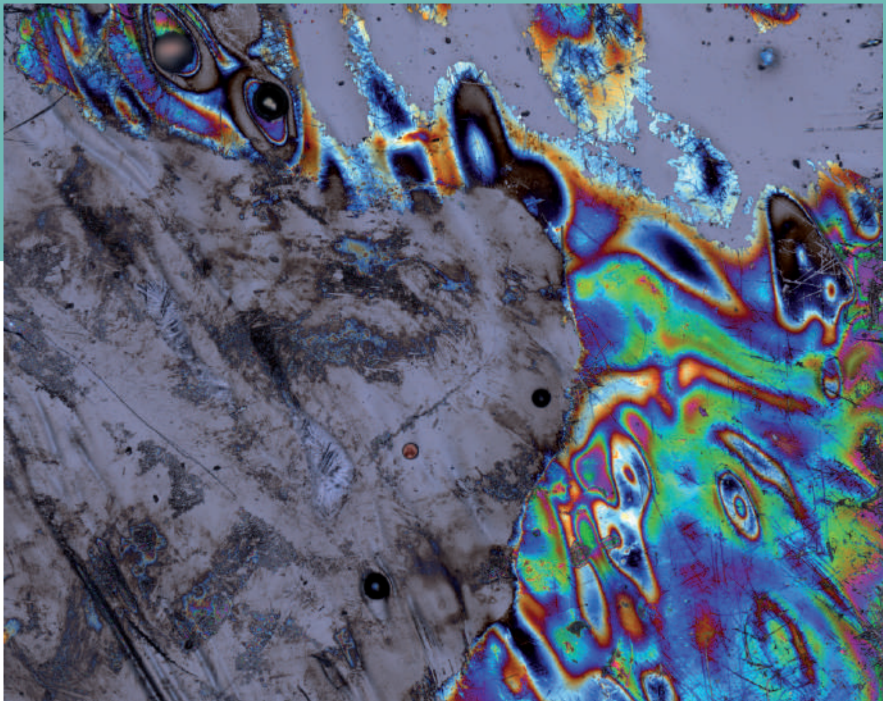
example, for continuous molding at low and very low viscosity. This is not only what enabled today's glass industry, but also what makes the glass route attractive to new ranges of materials: where crystal (and often particle) processing is not efficiently or sustainably feasible in the desired shapes and geometries, glass forming procedures are sought which offer fully new opportunities (such as most recently in the world of metal-organic frameworks).

The greatest leaps in glass innovation were and are still process-related (Figure 13.2). They have repeatedly and in a surprising continuity led to major societal changes, from the invention of the glass blowing pipe to industrial firing systems and continuous melting units, the manufacture of flat sheet, or high-purity silica glass and the advent of optical telecommunication. And this is notwithstanding parallel developments in related fields, albeit concerning glasses in different material classes: extrusion, injection molding and the many other ways of processing polymers or, e.g., the preparation of metallic glasses which has arrived at a crossroads towards innovating future processing methodology.

Order in disorder

The glassy nature implies their unexpectedly complex properties. For a glass of the very same chemical composition, vastly different physical properties can still be obtained as a function of the conditions at which the glass transition was conducted: many if not all properties of a glass depend on the cooling rate and pressure at which it was produced. This only adds to the effect of chemical composition and topology; in technological development, glasses have thus far largely evaded knowledge-based predictability and control of the more intricate combinations of properties such as required by modern material applications. Again, the single most important communality among all types of glass is their fundamental difference to crystalline materials: on the one hand, like liquids, glasses exhibit high macroscopic and microscopic homogeneity. They do not consist of grains, particles or different material phases. On the other hand, they exhibit

Figure 13.3. Order-disorder competition at a glass-like surface.
Source: L. Wondraczek.



a disordered atomic structure. As recognized already by Zachariasen in 1932, structural disorder creates an excess volume over the ordered state. This is visible when comparing crystalline and glassy forms of silica, but also neatly arranged versus freely moving objects. As a result, a disordered structure becomes non-affine at a certain length scale of observation; at this length scale, it comprises spatially fluctuating properties, thus, an end to structural homogeneity. Interestingly, many of the macroscopic characteristics we usually attribute to glasses rely on exactly this interplay of long and intermediate range homogeneity on the one side, and locality on the other: the way glasses break, the way they are optically transparent or the way they transmit sound.

Entering into a new phase of glass technology, it will be a major challenge to elucidate order in disorder. Universal descriptors and quantifiers will need to be deciphered towards the predictability of non-affinity beyond individual classes of materials [6]. These will allow for a new level of material design. Processing strategies adapted to such new generations of glasses will enable a world of novel glass products, further strengthening this exciting material's indispensable role towards a sustainable future.

References

[1] Hrabanus Maurus (780-856): *De rerum naturis*.

[2] Boccaletti, S. *et al.* (2006): “Complex networks: Structure and dynamics”, *Physics Reports*, 424: 175-308.

[3] Mauro, J. C. *et al.* (2016): “Accelerating the Design of Functional Glasses through Modeling”, *Chemistry of Materials*, 28: 4267-4277.

[4] Greaves, G. N. & Sen, S. (2007): “Inorganic glasses, glass-forming liquids and amorphizing solids”, *Advances in Physics*, 56: 1-166.

[5] Bennett, T. D. & Horike, S. (2018): “Liquid, glass and amorphous solid states of coordination polymers and metal-organic frameworks”, *Nature Reviews Materials*, 3: 431-440.

[6] Lerner, E. & Bouchbinder, E. (2021): “Low-energy quasilocalized excitations in structural glasses”, *The Journal of Chemical Physics*.

[7] Calahoo, C. & Wondraczek, L. (2020): “Ionic glasses: Structure, properties and classification”, *Journal of Non-Crystalline Solids: X*, 8: 100054.

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Julian R. Jones is Professor of Biomaterials at Imperial College London (UK) and is known for his work on bioactive glasses and hybrid biomaterials (“Bouncy Bioglass”). He has more than 170 journal articles and has co-edited three textbooks. He is a Fellow of the Society for Glass Technology and Fellow of the American Ceramics Society. He has received the Vittorio Gottardi Award from the International Commission on Glass (ICG), the Robert L. Coble Award (American Ceramics Society) and served as Chair of the Bioceramics Division of the American Ceramics Society in 2020-21. He is currently Chair of the ICG’s Coordinating Technical Committee.

Prof. Delia S. Brauer
Delia S. Brauer is Professor of Bioactive Glasses at the Otto Schott Institute of Materials Research, University of Jena, Germany. Her research focuses on glass-based materials for biomedical applications and glasses as therapeutic release devices. Structure-property correlations form a key part of her research. She is Chair of the Bioglass Technical Committee (TC04) and a member of the Education Technical Committee (TC23) of the International Commission on Glass, a Fellow of the Society of Glass Technology and a member of its Board of Fellows. In 2015, she won the Gottardi Prize of the International Commission on Glass.

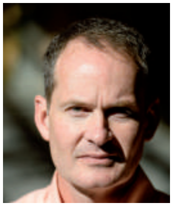
Prof. Himanshu Jain
Himanshu Jain is the T.L. Diamond Distinguished Chair Professor of Engineering and Applied Science, and Director of Institute for Functional Materials and Devices at Lehigh University. Over the past three decades he has focused on introducing new functionality and novel processing of glass, and making glass education available worldwide freely. Lately, he has been advocating for use-inspired research, and led the development of a new doctoral education model: Pasteur Partners Ph.D (P3) based on Industry-University partnerships. He is an author/editor of 12 patents, 10 books and over 400 research publications on glass science and technology.

Prof. Peng Shou

Prof. Peng Shou, academician of the Chinese Academy of Engineering (CAE), expert of glass new materials, is chief engineer of China National Building Material Group Co., Ltd., board chairman of China Triumph International Engineering Co., Ltd. and vice president of the Chinese Ceramic Society. Prof. Peng Shou has developed the world-class 30μm flexible ultra-thin glass (UTG), the first high-generation TFT-LCD glass substrate independently developed in China, the first Chinese neutral borosilicate glass tubing for vaccines, the CIGS power generation glass with the highest efficiency in the world, and a series of new glass materials. He has been awarded many prizes and received many weighty honors, including President Award of International Commission on Glass, Guanghua Engineering Science and Technology Award, Medal of Leadership in Advancement of Ceramic Technology of the American Ceramic Society, Ho Leung Ho Lee Foundation Science and Technology Innovation Award etc.

Prof. Giancarlo C. Righini
Giancarlo C. Righini is now a senior associate at the Nello Carrara Institute of Applied Physics (IFAC) of the National Research Council of Italy (CNR). Doctor in Physics at the University of Florence, he worked more than 40 years at CNR in Florence and Rome. Among various duties, he was Director of CNR National Group of Quantum Electronics, Research Director at IFAC, Director of CNR Department of Materials and Devices. After retiring from CNR, he was Director of the Enrico Fermi Center in Rome (2012-2016). He has always done experimental research, first in optical holography and signal processing, and then in fiber and integrated optics, with particular attention to glass and glass-ceramic materials. His publications record counts almost 600 articles, half of them in prestigious international journals; his name was included in the 2020 list of world's top 2% scientists in their main discipline, published by PLOS Biology. He was co-founder and then President of the Italian Society of Optics and Photonics (SIOF), Vice-President of the International Union of Pure and Applied Physics (IUPAP), Vice-President of the International Commission of Optics (ICO) and Secretary of the European Optical Society (EOS). He was Chair of the Technical Committee TC20 (Photonic glasses and optical fibers) of ICG (2012-2021). He is Fellow of SPIE (International Society for Optics and Photonics; 2003), SIOF (2003), EOS (2006), Optica (formerly OSA, The Optical Society; 2010), and Meritorious Member of SIF (Italian Physical Society; 2016).

Prof. Setsuhisa Tanabe
Setsuhisa Tanabe is a Professor of Material Chemistry at the Graduate School of Human and Environmental Studies, Kyoto University, Japan. He is the author of >270 original papers, >25 book chapters, and >40 review papers on rare-earth doped luminescent materials for up conversion lasers, optical fiber amplifier for telecommunication, LED phosphors and persistent phosphors. He has served as a plenary, keynote or invited speaker at >140 international conferences and at >200 domestic meetings & seminars. He is a Fellow of SPIE and ACerS. He now serves as an Editor of the *Journal of Luminescence* and is the Chair of the Japanese committee of the International Year of Glass 2022.



Prof. John Ballato

John Ballato is a professor of materials science and engineering at Clemson University, Clemson, SC, USA, where he is the inaugural holder of the Sirrine Endowed Chair in Optical Fiber. He has published more than 450 technical papers and holds 34 U.S. and foreign patents. He is a Fellow of the IEEE, American Association for the Advancement of Science (AAAS), American Physical Society (APS), Optica (formerly Optical Society of America, OSA), International Society of Optical Engineering (SPIE), and the American Ceramic Society (ACerS).

Arch. Sol Camacho

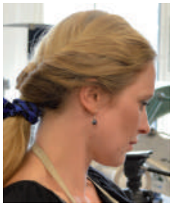
Sol is an architect, urban designer, and curator leading RADDAR (www.raddar.org), an innovative practice of architecture, research and design that operates in São Paulo and Mexico City. Among the most outstanding projects that Sol leads are the Project for the Restoration, Adaptation and New Building of the Pacaembu Stadium, in São Paulo. In 2018, Sol was the curator of the exhibition Muros de Ar for the Pavilion Brazilian from the International Architecture Exhibition of the Venice Biennale. Since 2017, she has been Cultural Director of Instituto Bardi/ Casa de Vidro (institutobardi.org), where she is responsible for exhibitions, cultural events and coordinator of Lina Bo Bardi's archive. Camacho has taught, written and lectured internationally on architecture, urban design and conservation at institutions such as PUC de Lima Peru, FADU de Montevideo Uruguay, Cornell, YALE, Harvard GSD, U. Michigan in USA, among others.

Eng. Erik Muijsenberg

Erik Muijsenberg is a Mechanical Engineering graduate of the University of Eindhoven from the Class of 1990. For the eight years following graduation, he was employed by the TNO Glass group in Eindhoven focusing his efforts in furnace modeling and glass melt technology. In 1997 he became the Glass Department leader. In 1998 he became a Glass Service B.V. Managing Director, first Glass Service subsidiary office in Maastricht, the Netherlands. After eleven years he moved to the Glass Service headquarters in the Czech Republic to become group Vice President. Glass Service employs over 100 engineers with offices worldwide including Czechia, Slovakia, Netherlands, Germany, UK, France, USA, Russia, China and Japan. In 1997 he was awarded, together with his former TNO colleagues, the Otto Schott Award. In 2012 he received the Adolf Dietzel Industry Award from the German Glass Society for his contribution to the development and acceptance of glass furnace modeling & optimization in the German glass industry. He was chosen as a Fellow member by the British Glass Society in 2014. Erik is also an active vice Chairman and past Chairmen of the Technical Committee 21, Furnace Design & Operations of the International Commission on Glass (ICG). As of 2016 Erik became an ICG Steering Committee member. In 2017 he became a Phoenix Award Committee member. Erik has been selected to become the next Vice Chair and future Chair of the Phoenix Award committee. Erik has actively promoted Industry 4.0 smarter model based furnace and forehearth control and CO_2 emission reductions to the Glass Industry for over twenty years.

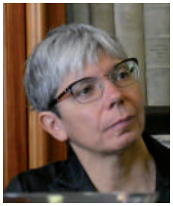
MSc. Michael delle Selve

As a Head Marketing and Communications, Michael comes with strong experience in Management, Communications and Marketing fields gained in European Institutions, Consulting Communications and Public Affairs Agencies, and Trade Associations. Since 2005, he has put his knowledge at the service of the European Container Glass Federation. He is now heading Communications, Marketing and Advocacy activities in Brussels and throughout Europe to support the industry in their business relationships with brands, retailers, consumers, and other stakeholders. Supported by the industry, he has shaped a common framework of Marketing and Advocacy activities and he coordinates their implementation with a network of 13 national teams. Michael holds an Executive Master's in International Association Management from the Solvay Brussels School Economics and Management, a University Degree in Foreign Languages from the University of Bari, Italy, acknowledged competences in integrated marketing and communications, social media, public affairs, management, and leadership. He speaks Italian, French and English (mother tongue level). He strives to keep constantly up to date by following training in the context of his current activities (e.g. social media communication, EU Public Affairs, mental coaching).



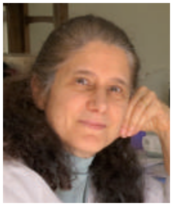
Dr. Jessamy Kelly

Dr. Jessamy Kelly is a glass artist and educator based in Edinburgh. She is a Lecturer in Glass, within the Design School at Edinburgh College of Art at the University of Edinburgh. She achieved her B.A. in Glass & Ceramics (2001) from the University of Sunderland, her M. Des. in Glass Design (2002) from Edinburgh College of Art, and her Ph.D. in Glass & Ceramics (2009) from the University of Sunderland. Her master's degree involved an Industrial placement at Edinburgh Crystal where she worked as an in-house glass designer until 2006. She has run her own studio glass business since graduating. Her glass work has been exhibited widely throughout the UK as well as internationally throughout Europe and the United States. Jessamy joined Edinburgh College of Art in 2012 and is currently the Programme Director of the Glass Master's degree, she has taken on numerous roles at ECA including Director of Postgraduate and Convenor of Postgraduate studies. Jessamy is guest editor of the MDPI Arts journal collection Topical Collection focused on Contemporary Glass Art: Materiality and Digital Technologies. Her research interests focus on materiality and making through material intersections, sustainable craft materials, new digital technologies and their relationship with analogue craft processes. Her creative practice examines the qualities of glass as an artistic, sustainable material and its ability to imitate or intersect with other materials. Her research outputs include a range of national and international exhibitions and peer-reviewed papers. She has collaborated on a number of interdisciplinary research projects and as a design facilitator and co-curator for museum-led design projects and exhibitions. She is the vice chair of the RAFT research group which explores the changing identity of craft practices and a Trustee of North Lands Creative and the Scottish Stained-Glass Trust.



Dr. Teresa Medici

Dr. Teresa Medici received a M.A. in Classical Archaeology at the University of Milan, Italy, and a Ph.D. in Archaeology at the University of Coimbra, Portugal. After a career in Italy as a contract archaeologist (1989-1993) and as a civil servant at the Museums and Cultural Heritage Department of the Regional Government of Lombardy (1994-2001), in 2002 she moved to Portugal. Joining the Research Unit VICARTE, Lisbon, she conducted original investigation on archaeological glass from Italy, Croatia, Spain, and Portugal, from Roman times to early 18th century, acquiring a vast knowledge on glass production, use and diffusion in Europe, with a special focus on in late medieval and early modern archaeological glass in the Iberian Peninsula. From 2015 Teresa is back in Italy, working on the accreditation scheme for museums at the Cultural Heritage Department of the Regional Government of Lombardy. She serves as the Chair of ICOM Glass IC (2019-2022), as a board member of the Italian Committee of the AIHV - Association Internationale pour l’Histoire du Verre, and as an Editorial Advisor for the *Journal of Glass Studies* (2020-2022).



Prof. Ana Candida Martins Rodrigues
Ana C. M. Rodrigues is a Full Professor at the Department of Materials Engineering in the Federal University of São Carlos, Brazil. Since her Ph.D., her main research topic has been glasses and glass-ceramics, especially electrical properties. Currently the Chair of the Technical Committee TC23 “Glass Education” of the International Commission of Glass, she is also the Coordinator of Education and Outreach of the Center for Research, Technology, and Education in Vitreous Materials (CeRTEV), an 11-year funded program by the Funding Agency from São Paulo State in Brazil, FAPESP.

Prof. Lothar Wondraczek

Lothar Wondraczek obtained his Ph.D with Honors from Clausthal University of Technology (Germany) in 2003, studying mid-infrared sensing of pollutants in industrial glass melting furnaces. After that, he joined Corning's European Technology Center in Avon, France, as a Senior Scientist. In 2008, he was one of the youngest German scientists to obtain a permanent professor position in the engineering sciences (Materials Science) at the University of Erlangen-Nuremberg. On his return to Germany, he started building-up what became a vibrant group of about 30 scientists, working on the broader area of glass science. In 2012, together with his group, he moved from Erlangen to Jena where he now holds the Chair of Glass Chemistry, a position unique in Germany. He has also been director of the Otto Schott Institute of Materials Research since 2016, and is a founding member of the board of Jena's Center of Energy and Environmental Chemistry. His research covers experimental glass science with a focus on the optical and mechanical properties of non-crystalline solids, aiming to bridge traditional borders between the different classes of materials. He has received several national and international research awards, among them the Weyl, Dietzel, Zachariasen and Gottardi awards for research on glassy materials, and ERC Consolidator and Proof-of-Concept grants in 2016 and 2021. He has also been leading various multi-laboratory research efforts, for example, a priority program of the German Science Foundation aiming to develop "Ultrastrong glasses", several international research and innovation actions sponsored by the European Commission, or, most recently, a focus action on stimulus-responsive materials supported through the Breakthrough-program of the Carl Zeiss Foundation. In 2022, he will serve as the program chair of the ICG's International Congress on Glass, to be held in Berlin, Germany. Wondraczek has also been a long-term chair of ICG's technical committee on glass mechanics.

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This book was printed in January 2022,
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COLECCIÓN**DIVULGACIÓN**

Welcome to the Glass Age

Interested to learn more of the global glass industry's story and what glass has given Society? Want to know about its environmental impact? Need to discover how glassy products can improve everyone's living conditions? You can uncover more in these pages: they target those with a non-specialist interest, they are richly illustrated and they focus on the UN 2030 goals.

The book's thirteen chapters cover such diverse topics as: the role of glass in health; energy conservation and generation; sustainability and communications, the transmission and accessing of information. Essays on Museums, Education, Art and architecture examine trends in design and use, and how glassy artefacts help to tackle welfare issues.

Of course, a little more than 200 pages cannot say it all. We particularly hope that you the reader will be encouraged to dream your own dreams and join the action yourselves.

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