



Glass 2045

Roadmap for the Decarbonisation of the German Glass Industry

About

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This study is an updated and extended version of Roadmap Glass 2045, originally published in 2022 by the Institute of Energy Economics and Rational Energy Use (IER) and the Federal Association of the German Glass Industry (Bundesverband Glasindustrie e.V.). The new roadmap is incorporating the significant changes in technology, economics, carbon markets, and resilience that the glass industry has been facing during the last years.

Welcome Note

The German glass industry is undergoing a profound transformation. Few other industries combine industrial value creation, technological innovation, and climate action to the same extent. Glass is indispensable in everyday life and, at the same time, a key material for the transformation and digitalisation of our economy: It protects food and medicines, improves the energy efficiency of buildings, enables renewable energy technologies, digital infrastructure, data centres and AI applications, and is also indispensable for numerous security and defence applications as well as other high-tech technologies. At the same time, the glass industry is one of the most energy-intensive basic materials industries, and decarbonising it represents one of the greatest industrial challenges of our time.

With the first “Glas 2045” roadmap, published in 2022, the Federal Association of the German Glass Industry (BV Glas e.V.) presented, for the first time, a scientifically substantiated transformation pathway for our industry. Technological developments clearly show that transformation is not static. It must be continuously reviewed and adapted to new technological, economic and political realities. This updated roadmap provides precisely that basis.

The results clearly show that no single decarbonisation pathway exists for the glass industry. Different production processes, products and locations require different solutions. Electrification will play a much larger role in the future than many assumed just a few years ago. At the same time, hydrogen, hybrid solutions, a stronger circular economy and, in the longer term, CCS and CCU applications will remain important components of

Vorwort

Die deutsche Glasindustrie befindet sich in einem tiefgreifenden Transformationsprozess. Kaum eine andere Branche steht so sehr für die Verbindung von industrieller Wertschöpfung, technologischer Innovation und Klimaschutz. Glas ist unverzichtbar für das tägliche Leben und zugleich ein Schlüsselmateriale für die Transformation und Digitalisierung unserer Wirtschaft: Es schützt Lebensmittel und Arzneimittel, macht Gebäude energieeffizienter, ermöglicht erneuerbare Energien, digitale Infrastrukturen, Rechenzentren und KI-Anwendungen und ist zudem unverzichtbar für zahlreiche Sicherheits- und Verteidigungsanwendungen sowie weitere Hightech-Technologien. Gleichzeitig gehört die Glasindustrie zu den energieintensiven Grundstoffindustrien, deren Dekarbonisierung zu den größten industriellen Herausforderungen unserer Zeit zählt.

Mit der ersten Roadmap „Glass 2045“, die 2022 veröffentlicht wurde, hat der Bundesverband Glasindustrie erstmals einen wissenschaftlich fundierten Transformationspfad für unsere Branche aufgezeigt. Die technischen Entwicklungen machen deutlich: Transformation ist kein statischer Prozess. Sie muss kontinuierlich überprüft und an neue technologische, wirtschaftliche und politische Realitäten angepasst werden. Mit der vorliegenden Aktualisierung der Roadmap schaffen wir genau diese Grundlage.

Die Ergebnisse zeigen eindrucksvoll, dass es nicht nur einen einzigen Dekarbonisierungspfad für die Glasindustrie gibt. Unterschiedliche Produktionsverfahren, Produkte und Standorte erfordern unterschiedliche Lösungen. Elektrifizierung wird künftig eine deutlich größere Rolle spielen als noch vor wenigen Jahren angenommen. Gleichzeitig bleiben Wasserstoff, Hybrid-

a successful transformation. It is therefore essential to remain open to different technologies and give companies the flexibility they need when making investment decisions.

However, technological feasibility alone is not sufficient. The transformation will only succeed if the political and economic framework conditions are appropriate. Our companies need competitive electricity prices and grid charges, timely expansion of electricity and hydrogen infrastructure, planning certainty over decades-long investment cycles, and effective protection against carbon leakage. Climate-neutral production must not result in industrial value creation leaving Germany and Europe. Our objective must be to reduce emissions, not industry.

The German glass industry is ready to contribute. Many companies are already investing in innovative melting technologies, energy efficiency and new production processes. These investments demonstrate that the industry is assuming responsibility and actively shaping the transition. At the same time, they highlight the enormous financial and infrastructural challenges associated with the transformation.

This roadmap is therefore intended not only as a scientific analysis, but also as a guide for policymakers, businesses and society. It outlines the available technological options, the infrastructure required in the future, and the political measures needed to safeguard the long-term competitiveness of a strategically important basic materials industry.

lösungen, eine stärkere Kreislaufwirtschaft sowie perspektivisch auch CCS- und CCU-Anwendungen wichtige Bausteine einer erfolgreichen Transformation. Entscheidend ist dabei, technologieoffen zu bleiben und den Unternehmen die notwendige Flexibilität bei ihren Investitionsentscheidungen zu ermöglichen.

Ebenso deutlich wird aber auch: Die technologische Machbarkeit allein reicht nicht aus. Die Transformation wird nur dann gelingen, wenn die politischen und wirtschaftlichen Rahmenbedingungen stimmen. Unsere Unternehmen benötigen wettbewerbsfähige Strompreise und Netzkosten, den rechtzeitigen Ausbau der Strom- und Wasserstoffinfrastruktur, Planungssicherheit über Investitionszyklen von Jahrzehnten hinweg sowie einen wirksamen Schutz vor Carbon Leakage. Klimaneutrale Produktion darf nicht dazu führen, dass die industrielle Wertschöpfung Deutschland und Europa verlässt. Unser Ziel muss sein, Emissionen zu reduzieren – nicht die Industrie.

Die deutsche Glasindustrie ist bereit, ihren Beitrag zu leisten. Viele Unternehmen investieren bereits heute in innovative Schmelztechnologien, Energieeffizienz und neue Produktionsverfahren. Diese Investitionen zeigen, dass die Branche Verantwortung übernimmt und den Wandel aktiv gestaltet. Gleichzeitig machen sie deutlich, welche enormen finanziellen und infrastrukturellen Herausforderungen mit der Transformation verbunden sind.

Die vorliegende Roadmap versteht sich daher nicht nur als wissenschaftliche Analyse, sondern auch als Orientierung für Politik, Wirtschaft und Gesellschaft. Sie zeigt auf, welche technologischen Möglichkeiten bestehen, welche Infrastruktur künftig benötigt wird und welche politischen Maßnahmen erforderlich sind, um die Wettbewerbsfähigkeit einer strategisch wichtigen Grundstoffindustrie langfristig zu sichern.

My sincere thanks go to the Institute of Energy Economics and Rational Energy Use (IER) at the University of Stuttgart, in particular Professor Dr. Peter Radgen and Alexandra Löwenstein, for their scientific support and excellent cooperation. I would also like to thank the numerous member companies of the Federal Association of the German Glass Industry, which contributed their data, expertise and practical experience to this roadmap. Without this commitment, such a well-founded analysis would not have been possible.

Christiane Nelles
Managing Director BV Glas e.V.

Mein herzlicher Dank gilt dem Institut für Energiewirtschaft und Rationelle Energieanwendung (IER) der Universität Stuttgart, insbesondere Herrn Prof. Dr. Peter Radgen und Frau Alexandra Löwenstein, für die wissenschaftliche Begleitung und die hervorragende Zusammenarbeit. Ebenso danke ich den zahlreichen Mitgliedsunternehmen des Bundesverbandes Glasindustrie e.V., die ihre Daten, ihre Expertise und ihre praktischen Erfahrungen in diese Roadmap eingebracht haben. Ohne dieses Engagement wäre eine derart fundierte Analyse nicht möglich gewesen.

Christiane Nelles
Hauptgeschäftsführerin BV Glas e.V.

Preface

The transformation of the German glass industry remains central to both industrial and climate policy. As an energy-intensive basic materials industry, the sector is a key part of numerous value chains and supplies products for buildings, renovation, packaging, pharmaceuticals, mobility, infrastructure, and a broad range of technical applications. At the same time, the German glass industry is strategically important. Germany is Europe's largest glass producer and the fourth-largest worldwide. German glass products hold a strong technological position, and the sector plays a central role in the European glass supply.¹

The German Glass Industry Association commissioned the Institute of Energy Economics and Rational Energy Use at the University of Stuttgart to develop an initial roadmap outlining possible transformation pathways for the sector to achieve the 2045 greenhouse gas reduction targets while maintaining the sector's economic strength. Since the roadmap's first publication in 2022, technology, regulation, and the economic framework have changed significantly. Therefore, an update of the initial study was initiated by BV Glas e.V. to revise the roadmap and assess the developments that have occurred since its publication. The study considered technological progress, lessons learned from pilot and demonstration projects, and evolving energy and climate policy frameworks at the national and European levels. As in the original roadmap, the study builds on a site-by-site assessment of the industry and on company-provided data. In addition, expert interviews helped incorporate the latest developments. We sincerely thank everyone involved for their trust in us and constructive cooperation.

Decarbonising the glass industry will require additional costs, substantial investment, and demanding implementation processes. At the same time,

circularity remains an important pillar of the sector's climate strategy. Glass is, in principle, fully recyclable without loss of quality, and increasing the share of cullet used reduces both energy demand and process-related emissions by lowering the need for virgin carbonate raw materials. Sector strategies therefore underline that circularity is a critical part of decarbonisation, but not a substitute for industrial and climate policies that decarbonise process energy itself.²

The main lever for reducing energy-related emissions remains the transition to low-carbon energy carriers. The central technological options currently under discussion and development are electrification, hydrogen-based technologies, and hybrid concepts combining both. At the same time, the sector faces structural constraints: glass production processes must run continuously, ensuring thermal stability is essential for product quality, and short-term load flexibility is limited. This means the transition's success depends not only on furnace technologies but also on a reliable, continuous electricity supply and, depending on the pathway, on the availability of hydrogen and CO₂ transport and storage infrastructure.

An even greater challenge is reducing process-related emissions from decomposing carbonate-based raw materials during glass melting. Fuel switching or electrification cannot eliminate these emissions. Options such as higher cullet shares, alternative raw materials, and, particularly for flat glass, carbon capture combined with CO₂ transport and utilisation and/or storage therefore need to be considered, depending on segment-specific requirements and local conditions. Deep decarbonisation will likely require a combination of energy substitution, circularity, and complementary solutions for residual process emissions.

Over the past four years, the economic environment for the German glass industry has deteriorated considerably. High energy and emission costs, weak demand, and persistent uncertainty regarding future market and policy developments have increased the pressure on companies. The transformation must therefore occur amid already challenging competitive conditions.

Against this background, maintaining the competitiveness of glass production in Germany is central to a successful transformation. The transition to low-carbon production technologies will require substantial investment and, in many cases, higher operating expenditures. A durable, increasingly market-driven transformation can therefore emerge only if process-related energy costs for low-carbon electricity and hydrogen become competitive with those of natural gas. As long as a significant cost gap persists, investment support alone will not be sufficient to trigger a broad transformation of the sector.

Appropriate framework conditions will be required to address additional operating costs and to provide companies with sufficient planning certainty. The transformation of the German glass industry must therefore be understood not only as a technological challenge, but equally as a question of energy costs, infrastructure availability, investment conditions, and industrial competitiveness.

This roadmap is therefore intended as both an orientation framework and a reference document for the sector, while also identifying the regulatory and policy support required for its transformation. It aims to provide transparency on technological options, structural dependencies, and timing constraints, particularly those linked to furnace lifetimes and reinvestment cycles, as well as the availability of the required electricity, hydrogen, and CO₂ transport infrastructure. It also highlights trade-offs and derives priorities for infrastructure, funding, research, and policy action.

The glass industry can transform successfully only through close interaction among companies, policy-makers, energy suppliers, infrastructure operators, and research institutions. As BV Glas e.V. stresses, the glass industry's competitiveness in Germany will depend decisively on framework conditions that support the transition to low- or carbon-free technologies, especially by expanding infrastructure for a continuous supply of green electricity and hydrogen.

Alexandra Löwenstein

Prof. Dr. Peter Radgen

Table of Contents

About.....	i
Welcome Note Vorwort	ii
Preface.....	v
Table of Contents	vii
Executive Summary.....	1
Zusammenfassung	6
Introduction and Objectives of the Roadmap	13
1 Overview of the German Glass Industry	15
1.1 The Role of the Glass Industry in Industrial Value Chains.....	15
1.2 Current Challenges for the Glass Industry	16
1.2.1 Industrial Challenges.....	16
1.2.2 Technical Challenges	16
1.2.3 Economic Challenges	16
1.2.4 Decarbonisation Challenges.....	17
1.2.5 Societal and Regulatory Challenges	17
2 Current Situation and Need for Action	18
2.1 Developments since the first Glass Roadmap published in 2022	18
2.2 Economic and Political Framework Conditions	20
2.3 Technological Developments	21
3 Update of the Transformation Pathways.....	26
3.1 Methodological Approach.....	26
3.2 Baseline and Core Assumptions	27
3.2.1 Optional Integration of CCS/CCU	31
3.2.2 Improvement of Circularity	32
4 Transformation Pathways	33
4.1 BAU Pathway.....	33
4.2 Electrification Pathway	36

4.3	Hydrogen Pathway	40
4.4	Hybrid Pathway	43
4.4.1	Glass Industry as a whole.....	43
4.4.2	Hollow Glass.....	47
4.4.3	Flat Glass	51
4.4.4	Technical & other Glass.....	54
4.4.5	Carbon Capture Storage and Utilization in the hybrid pathway.....	57
4.5	Overall Comparison.....	64
4.5.1	Contribution to the decarbonisation of the Glass industry	64
4.5.2	Energy demand and infrastructure requirements	65
4.5.3	Overall Conclusions.....	67
5	Political and Regulatory Framework Conditions	69
5.1	Funding Instruments and Legal Developments	69
5.2	The Importance of Infrastructure Planning Security.....	70
6	Outlook and Recommendations	71
6.1	Key Results	71
6.2	Recommendations for Policymakers and the Glass Industry	72
6.2.1	Recommendations for Policymakers	73
6.2.2	Recommendations for the glass Industry	76
6.2.3	Possible Next Steps	78
	List of Figures	80
	List of Tables	82
7	References	83
8	Annex	85
8.1	Assessment of the Current Status.....	85
8.1.1	Structure of the Glass Industry	85
8.1.2	Online Data Collection	85
8.1.3	Summary of Site Data	86
8.1.4	Overview of Ongoing Research and Development Projects	87
8.1.5	Patent Analysis	87

Executive Summary

The German glass industry is undergoing a fundamental transformation. As an energy-intensive materials industry, it supplies key value chains, including construction, packaging, pharmaceuticals, mobility, infrastructure and a broad range of technical applications. At the same time, glass production generates substantial greenhouse-gas emissions because it requires continuous high-temperature process heat and uses carbonate-based raw materials. The sector must therefore reconcile climate neutrality with industrial competitiveness, product quality, and supply security.

This transformation is taking place against an increasingly challenging economic backdrop. Any decarbonisation strategy must therefore address not only technical feasibility and emission reductions, but also glass production's ability to remain economically viable in Germany.^{1,3}

Compared with the first glass-industry roadmap published in 2022, this study reflects technological progress, recent policy and infrastructure developments, new site-level information, and the sector's current economic situation. The analysis is based on 2024 baseline data and combines a site-specific assessment of the German glass industry with scenario-based modelling up to 2045. Reflecting the sector's heterogeneity, the roadmap differentiates between hollow glass, flat glass, technical glass, and other glass. Together, these segments accounted for approximately 95% of Germany's glass production by tonnage in 2024, excluding stone wool. It does not provide comprehensive statements on glass-fibre production, flat-glass finishing, or other downstream activities outside the scope of the BV Glas member companies covered by the analysis. Consider this system boundary when comparing the results with broader sectoral statistics or emissions inventories.

The analysis confirms that no universal decarbonisation route exists for the German glass industry. Transformation will instead be site- and segment-specific, depending on a tailored mix of electrification, hydrogen-based furnace concepts, hybrid solutions, circularity measures, raw-material strategies, and potentially carbon-management options for residual process emissions. The feasibility of these options depends not only on furnace technology but also on technological maturity, electricity infrastructure, hydrogen availability, furnace-rebuild cycles, energy prices, regulatory certainty, and access to suitable financing and support mechanisms.

Although the pathway analysis focuses on transforming melting furnaces, the site-level energy balances also include feeders, forming processes and annealing lehrs. Their energy consumption is therefore already reflected in the modelled final energy demand. Other auxiliary processes, particularly compressed-air generation and drives, are not explicitly modelled and must be considered separately in site-level implementation planning. This includes assessing their remaining fossil-fuel use, additional electricity requirements and associated infrastructure needs.

The comparison in **Table 1** highlights an important modelling result: the three industry transformation pathways reach the same residual-emission level in 2045, but through fundamentally different technology and energy systems. The best pathway therefore cannot be chosen based on 2045 emissions alone. Energy demand, infrastructure requirements, technological readiness, investment needs and operating costs are equally important.

The annual emission trends over the modelling period illustrates this distinction. The Electrification, Hydrogen and Hybrid Pathways reduce emissions to

0.492 Mt CO₂/a in 2045, an 86.5% reduction from 2024. The remaining emissions are process-related and come from decomposing carbonate raw materials. The CCS Pathway reduces residual emissions further to 0.344 Mt CO₂/a by capturing both combustion- and process-related CO₂ from CCS-equipped flat-glass furnaces.

However, because CCS deployment can begin only in 2040 due to infrastructural availability and the assumed furnace-rebuild cycles, its contribution to cumulative emission reductions is visible but limited.

Table 1 Key results of the transformation pathways in 2045

Pathway	CO ₂ emissions [Mt CO ₂ /a]	Total final energy demand [PJ/a]	Electricity [PJ/a]	Hydrogen [PJ/a]	Natural gas [PJ/a]	Cumulative plant-level investment [€ bn]
BAU	2.36	43.8	7.6	0	36.2	1.84
Electrification	0.492	33.3	26	7.3	0	5.64
Hydrogen	0.492	38.7	14.5	24.2	0	3.76
Hybrid	0.492	36.8	24.8	12	0	6.15
CCS	0.344	35.5	23.1	2.2	10.2	6.11

Note: Investment values represent cumulative plant-level investment from 2024 up to 2045. External electricity-grid expansion, hydrogen production and transport infrastructure, and external CO₂ transport and geological storage infrastructure are partially included for flat glass.

The pathways also require different energy systems, as shown in **Table 2**. Electrification results in the highest electricity demand, whereas the Hydrogen-based Pathway requires the largest hydrogen supply. The Hybrid Pathway splits its energy demand between electricity and hydrogen, reducing dependence on a single future energy carrier, but it requires both infrastructures to develop in parallel. The CCS Pathway introduces a third infrastructure dimension: in addition to electricity and continued natural-gas supply, flat-glass sites require access to CO₂ conditioning, transport and permanent storage infrastructure.

Interpret the investment estimates as model results rather than a complete representation of system-wide transformation expenditure. They include furnace replacement or modification and the technology-specific infrastructure within the production site up to the interface with external electricity, hydrogen or CO₂ infrastructure. External transmission networks, hydrogen production and transport sys-

tems, CO₂ transport networks and geological storage capacity are not represented. Actual expenditure at individual sites may therefore be higher or lower.

Table 2 Main characteristics and infrastructure requirements of the transformation pathways

Pathway	Main energy-system characteristic	Principal infrastructure requirement	Key advantage	Main implementation challenge
Electrification	Strong shift towards electricity	Grid reinforcement and higher site-connection capacity	Lowest final energy demand	Grid capacity, continuous electricity supply and competitive electricity prices
Hydrogen	Strong substitution of natural gas by hydrogen	Hydrogen production, transport and regional distribution	Lowest plant-level CAPEX of the three industry transformation pathways	Availability and cost of hydrogen
Hybrid	Combination of electricity and hydrogen	Parallel development of electricity and hydrogen infrastructure	Diversification across two energy carriers	Dependence on two infrastructure systems developing in parallel
CCS	Oxy-fuel flat-glass production combined with CO ₂ capture	CO ₂ conditioning, transport and permanent geological storage	Lowest residual emissions	CO ₂ infrastructure, OPEX for capture, and use of natural gas
BAU	Continued reliance on conventional furnace technologies and fossil fuels	Existing gas and electricity infrastructure	No additional transformation effort	High emissions and continued fossil-fuel dependency

Table 3 shows significant differences in required investment across pathways. The BAU Pathway requires €1.84 billion in cumulative baseline reinvestment through 2045. Among the three industry transformation pathways, the Hydrogen-based Pathway has the lowest cumulative plant-level investment requirement (€3.76 billion), followed by Electrification (€5.64 billion) and Hybrid (€6.15 billion). The CCS Pathway requires €6.11 billion. Similar plant-level CAPEX does not, however, imply similar total system costs: hydrogen-based transformation remains highly exposed to hydrogen prices and infrastructure development; Electrification to electricity prices and grid requirements; Hybrid to the parallel development of two energy infrastructures; and CCS to natural-gas and oxygen costs, as well as capture OPEX and CO₂ transport and storage charges.

Table 3 Cumulative plant-level investment requirements up to 2045 by pathway

Pathway	Cumulative plant-level investment 2045	Additional investment compared to BAU
BAU	€1.84 bn	–
Hydrogen	€3.76 bn	€1.92 bn
Electrification	€5.64 bn	€3.80 bn
CCS	€6.11 bn	€4.27 bn
Hybrid	€6.15 bn	€4.31 bn

Future operating costs are therefore at least as important as upfront capital expenditure. A technically feasible transformation will be economically sustainable only if the resulting energy and carbon-management costs keep glass production competitive over the furnace's operating lifetime. For the glass industry, this means low-carbon electricity and

hydrogen must compete with natural-gas-based process energy, or policy instruments must reliably bridge the remaining cost gap.

Across the transformation pathways, residual emissions in 2045 are dominated by process-related CO₂ emissions from carbonate dissociation. Even deep decarbonisation of process energy therefore does not fully eliminate emissions. Increased cullet uses and alternative raw materials remain important complementary measures, but availability, sorting quality, purity requirements, and product-specific or regulatory constraints limit their potential. These limitations are particularly relevant for flat glass and technical glass. Carbon capture and utilisation or storage should therefore be prepared as complementary options for residual emissions where technically, economically and infrastructurally feasible.

The pathway comparison highlights that the principal barriers to decarbonisation are not purely technological. Electrification requires sufficient grid capacity, higher site-connection capacities and reliable electricity supply at internationally competitive prices. Hydrogen-based transformation depends critically on future hydrogen production, imports, transport and regional distribution. Hybrid concepts require both systems to develop in parallel. CCS adds the requirement for CO₂ capture, conditioning, transport and permanent storage.

Technological maturity is equally important. The existence of a technology at pilot or demonstration scale should not be interpreted as evidence that it is already commercially available for all glass products and furnace sizes. This is particularly relevant for large-scale flat-glass production, where furnace capacity, process stability and strict product-quality requirements continue to constrain the degree of electrification that can be realised. The roadmap therefore links technology deployment to realistic furnace-rebuild cycles and differentiates between glass segments rather than assuming a uniform transformation of the entire sector.

Planning for electricity, hydrogen, and CO₂ infrastructure security; competitive energy prices; long-

term funding instruments; support for additional operating costs; and credible solutions for residual process emissions are therefore central conditions for implementation. These requirements must be available in practice at the relevant production sites and when individual furnaces reach their rebuild dates.

The roadmap highlights the importance of effective carbon leakage protection. The definitive regime of the EU Carbon Border Adjustment Mechanism entered into force on 1 January 2026, but it does not cover glass products. CBAM therefore does not currently provide direct carbon-leakage protection for the glass industry. Additional safeguards remain necessary to prevent decarbonisation requirements from shifting production towards regions with lower energy prices or weaker carbon regulation rather than reducing global emissions. This concern is particularly relevant given the recent deterioration in the German glass industry's economic situation and the high sensitivity of future low-carbon production to electricity, hydrogen, CO₂, and infrastructure costs.

The roadmap consequently identifies several priorities for action summarised in **Table 4**. For policy-makers, these include accelerating electricity and hydrogen infrastructure, improving the economics of industrial electrification, maintaining stable long-term support instruments, addressing operating-cost risks, strengthening circularity and raw-material strategies within their technical limits, developing a realistic carbon-management framework and ensuring effective carbon-leakage protection.

For the glass industry, the recommendations include aligning transformation planning with furnace-rebuild cycles, developing site-specific pathway strategies, treating electricity supply and grid capacity as core industrial planning issues, assessing hydrogen selectively, using hybrid concepts strategically where technological or infrastructure uncertainty remains high, incorporating downstream-process conversion into site-level planning and pre-

paring early for the management of residual process emissions. A central economic condition applies across all pathways: a self-sustaining transformation can emerge only if process-energy costs for low-carbon electricity and hydrogen become competitive with natural-gas-based production, or if policy instruments reliably compensate for the remaining cost gap. Competitive low-carbon energy prices and support for both CAPEX and additional OPEX are therefore central conditions for industrial decarbonisation without loss of competitiveness. Overall, the updated roadmap shows that deep decarbonisation of the German glass industry by 2045 is technically possible, but it will not happen automatically. The pathways differ substantially in electricity demand, hydrogen requirements, investment needs, infrastructure dependencies and implementation risks. Electrification is becoming increasingly

important across the sector; hydrogen is used more selectively where complete electrification remains technically constrained; hybrid solutions combine technologies and manage infrastructure uncertainty; and CCS offers an additional option for reducing residual emissions, especially from large-scale flat-glass production.

The decisive challenge is no longer identifying possible technologies alone. It is creating the industrial, infrastructural, economic, and regulatory conditions for companies to implement these technologies at the relevant furnace-rebuild dates while maintaining internationally competitive glass production in Germany and Europe.

Table 4 Priority actions for policymakers and the German glass industry

Policyholders	Glass Industry
Accelerate electricity-grid reinforcement and site connections.	Align transformation planning with furnace-rebuild cycles.
Support development of hydrogen production, transport and regional distribution	Develop site-specific transformation strategies.
Establish reliable CO ₂ transport and storage infrastructure for industrial CCS.	Treat electricity supply and grid capacity as core strategic elements.
Improve the economics of industrial electrification.	Assess hydrogen selectively, based on technical and local infrastructure developments.
Provide stable long-term investment support for instruments.	Use hybrid concepts strategically where technological or infrastructure uncertainty remains high.
Address additional operating-cost burdens during the transition	Include downstream and auxiliary processes in site-level transformation planning
Strengthen circularity and raw-material strategies within technical limits.	Prepare early for managing residual process emissions.
Ensure effective carbon-leakage protection.	Integrate energy-price and infrastructure risks into investment decisions.

Zusammenfassung

Die deutsche Glasindustrie steht vor einer grundlegenden Transformation. Als energieintensive Grundstoffindustrie ist sie ein wichtiger Zulieferer für zentrale Wertschöpfungsketten, darunter die Bauwirtschaft, die Verpackungsindustrie, die Pharmazie, die Mobilität, die Infrastruktur sowie zahlreiche technische Anwendungen. Gleichzeitig ist die Glasherstellung aufgrund der kontinuierlichen Bereitstellung von Prozesswärme bei hohen Temperaturen sowie des Einsatzes karbonathaltiger Rohstoffe mit erheblichen Treibhausgasemissionen verbunden. Die Branche steht daher vor der Herausforderung, Klimaneutralität mit industrieller Wettbewerbsfähigkeit, Produktqualität und Versorgungssicherheit zu vereinbaren.

Diese Transformation erfolgt unter zunehmend schwierigen wirtschaftlichen Rahmenbedingungen. Im Jahr 2025 ging die deutsche Glasproduktion um 0,9 % auf 6,60 Mio. t zurück, während der Branchenumsatz um 4,8 % auf 10,71 Mrd. € sank. Die Zahl der Beschäftigten verringerte sich um 4,9 % auf 51.000. Zusammen mit dem Rückgang des Branchenumsatzes um 12,67 Mrd. € im Jahr 2022 auf 10,71 Mrd. € im Jahr 2025 verdeutlicht diese Entwicklung den erheblichen Wettbewerbsdruck, während gleichzeitig die Transformation der Branche erfolgen muss. Eine Dekarbonisierungsstrategie muss daher nicht nur die technologische Machbarkeit und die Emissionsminderung, sondern auch die wirtschaftliche Tragfähigkeit der Glasproduktion in Deutschland berücksichtigen.^{1,3}

Die vorliegende Roadmap aktualisiert die erste Roadmap für die Glasindustrie aus dem Jahr 2022. Sie berücksichtigt technologische Fortschritte, aktuelle politische und infrastrukturelle Entwicklungen, neue standortspezifische Informationen sowie die gegenwärtige wirtschaftliche Situation der Branche. Die Analyse basiert auf Daten des Basisjahres 2024 und kombiniert eine standortspezifische Betrachtung

der deutschen Glasindustrie mit einer szenariobasierten Modellierung bis 2045. Aufgrund der Heterogenität der Branche wird zwischen Behälterglas, Flachglas und technischem Glas unterschieden. Die betrachteten Glassegmente machten im Jahr 2024 rund 95 % der deutschen Glasproduktion aus, gemessen an der Produktionstonnage und ohne Berücksichtigung von Steinwolle. Für die Glasfaserproduktion, die Flachglas Veredelung sowie weitere nachgelagerte Prozesse außerhalb der in der Analyse berücksichtigten BV-Glas-Mitgliedsunternehmen können keine umfassenden Aussagen getroffen werden. Diese Systemgrenze ist insbesondere beim Vergleich mit umfassenderen Branchenstatistiken oder Emissionsinventaren zu berücksichtigen.

Die Analyse bestätigt, dass es keinen einheitlichen Dekarbonisierungspfad für die deutsche Glasindustrie gibt. Die Transformation wird vielmehr standort- und segmentspezifisch erfolgen und auf einer differenzierten Kombination aus Elektrifizierung, wasserstoffbasierten Wannenkonzepten, hybriden Lösungen, Kreislaufwirtschaft, Rohstoffstrategien sowie potenziell ergänzenden Carbon-Management-Optionen für verbleibende Prozessemissionen beruhen. Die Umsetzbarkeit dieser Optionen hängt nicht allein von der Wannentechnologie ab, sondern auch vom technologischen Reifegrad, der Strominfrastruktur, der Verfügbarkeit von Wasserstoff, den Wannenrevisionszyklen, den Energiepreisen, der regulatorischen Planungssicherheit sowie dem Zugang zu geeigneten Finanzierungs- und Förderinstrumenten.

Obwohl die Transformation der Schmelzwannen im Mittelpunkt der Pfadanalyse steht, werden in den standortbezogenen Energiebilanzen auch die Energieverbräuche der Feeder, der Formgebung und der Kühlbahnen berücksichtigt. Diese Prozesse sind somit bereits im modellierten Endenergiebedarf enthalten. Weitere Hilfsprozesse, insbesondere die

Druckluftherzeugung und die Antriebe, werden hingegen nicht explizit modelliert und müssen bei der standortspezifischen Transformationsplanung gesondert berücksichtigt werden. Dies umfasst insbesondere den fortbestehenden Einsatz fossiler Energieträger, zusätzliche Strombedarfe sowie die damit verbundenen Infrastrukturanforderungen. Zur Analyse möglicher Entwicklungen vergleicht die Roadmap vier Pfade für die gesamte Glasindustrie: den Referenz-/BAU-Pfad, den Elektrifizierungspfad, den Wasserstoffpfad und den Hybridpfad. Ergänzend wird für die Flachglas Produktion ein CCS-Pfad untersucht, bei dem CO₂ am Produktionsstandort abgeschieden und anschließend zur dauerhaften geologischen Speicherung transportiert wird. Der Referenz-/BAU-Pfad beschreibt eine Fortführung der bestehenden Technologiestruktur ohne einen systematischen Übergang zu CO₂-armen Schmelztechnologien. Erdgas bleibt der dominierende Energieträger. Die gesamten CO₂-Emissionen sinken von 3,64 Mio. t CO₂/a im Jahr 2024 auf 2,36 Mio. t CO₂/a im Jahr 2045. Dieser Rückgang ist vor allem auf die im Modell angenommene Verringerung der Produktionskapazitäten sowie auf die fortschreitende Dekarbonisierung des Stromsektors zurückzuführen und nicht auf eine strukturelle Transformation des Wannenbestands.

Der Elektrifizierungspfad geht davon aus, dass die Dekarbonisierung hauptsächlich durch den steigenden Stromverbrauch der Glasschmelzen erreicht wird. Konventionelle erdgasbefeuerte Wannen werden schrittweise durch vollelektrische Wannen sowie stark elektrifizierte Hybridkonzepte ersetzt. Der Erdgasbedarf sinkt bis 2045 auf 0, während der Strombedarf 26,0 PJ/a beträgt. Gleichzeitig verbleibt in Wannenkonfigurationen ein Wasserstoffbedarf von 7,3 PJ/a, der im betrachteten Zeitraum nicht vollständig elektrifiziert wird. Der gesamte Endenergiebedarf beträgt 33,3 PJ/a und ist damit der niedrigste unter den Transformationspfaden. Die CO₂-Emissionen sinken bis 2045 auf 0,492 Mio. t CO₂/a, während sich die kumulierten Investitionen auf Standortebene auf 5,64 Mrd. € belaufen.

Der Wasserstoffpfad geht davon aus, dass die Dekarbonisierung hauptsächlich durch die Substitution von Erdgas durch Wasserstoff im Schmelzprozess erfolgt. Auch hier sinkt der Erdgasbedarf bis 2045 auf null. Der Wasserstoffbedarf steigt auf 24,2 PJ/a, der Strombedarf auf 14,5 PJ/a. Der gesamte Endenergiebedarf beträgt 38,7 PJ/a. Damit weist dieser Pfad mit deutlichem Abstand den höchsten Wasserstoffbedarf aller Transformationspfade auf. Die CO₂-Emissionen sinken auf 0,492 Mio. t CO₂/a. Mit kumulierten Investitionen auf Standortebene von 3,76 Mrd. € weist der Wasserstoffpfad zugleich den geringsten Investitionsbedarf unter den drei Transformationspfaden auf. Seine Umsetzbarkeit hängt jedoch in besonderem Maße von der rechtzeitigen Verfügbarkeit einer Wasserstoffinfrastruktur, von ausreichenden Versorgungsmengen sowie von Wasserstoffpreisen ab, die eine wettbewerbsfähige Glasproduktion ermöglichen.

Der Hybridpfad maximiert keine einzelne Technologie- oder Energieträgeroption, sondern bildet eine differenzierte Transformationsstrategie ab, in der Elektrifizierung und wasserstoffbasierte Wannenkonzepte entsprechend den technischen Bedingungen der jeweiligen Glassegmente und Produktionsstandorte kombiniert werden. Der Pfad wird daher zusätzlich in Teilpfade für Behälterglas, Flachglas und technisches Glas unterteilt. Im Jahr 2045 beträgt der Strombedarf 24,8 PJ/a und der Wasserstoffbedarf 12,0 PJ/a, während Erdgas vollständig aus dem Energiemix verschwindet. Der gesamte Endenergiebedarf beträgt 36,8 PJ/a, und die CO₂-Emissionen sinken auf 0,492 Mio. t CO₂/a. Die kumulierten Investitionen auf Standortebene belaufen sich auf 6,15 Mrd. €. Damit ist der Hybridpfad in der aktuellen Modellierung der kapitalintensivste der drei Transformationspfade. Dieser Wert resultiert aus der Abfolge unterschiedlicher Technologien, den angenommenen Wannenlebensdauern sowie den damit verbundenen Revisionszyklen und sollte daher nicht allein als Folge des endgültigen Strom- oder Wasserstoffbedarfs interpretiert werden.

Der ergänzende CCS-Pfad adressiert die Prozessmissionen als Dekarbonisierungshürde und wird spezifisch für die Flachglas Produktion untersucht. Ein Wechsel des Energieträgers kann fossile Verbrennungsemissionen beseitigen, nicht jedoch die bei der Zersetzung karbonathaltiger Rohstoffe entstehenden CO₂-Emissionen. Im CCS-Pfad werden daher erdgasbetriebene Oxy-Fuel-Wannen in der Flachglas Produktion mit CO₂-Abscheidung und anschließendem Transport zur dauerhaften geologischen Speicherung kombiniert. Für die gesamte Glasindustrie werden im CCS-Pfad im Jahr 2045 23,1 PJ/a Strom, 2,2 PJ/a Wasserstoff und 10,2 PJ/a Erd-

gas benötigt. Der gesamte Endenergiebedarf beträgt damit 35,5 PJ/a. Die verbleibenden CO₂-Emissionen sinken auf 0,344 Mio. t CO₂/a, was einer Reduktion von 90,6 % gegenüber dem Basisjahr 2024 entspricht. Die kumulierten Investitionen auf Standortebe-
tragen 6,11 Mrd. €. Die Wirtschaftlichkeit dieses Pfads hängt jedoch zusätzlich von den Betriebskosten und dem Energiebedarf der CO₂-Abscheidung sowie von der rechtzeitigen Verfügbarkeit von CO₂-Transport- und dauerhaften Speicherinfrastrukturen ab.⁴

Tabelle 5 Zentrale Ergebnisse der Transformationspfade im Jahr 2045

Pfad	CO ₂ - Emissionen [Mt CO ₂ /a]	Endenergiebedarf [PJ/a]	Strom [PJ/a]	Wasserstoff [PJ/a]	Erdgas [PJ/a]	Kumulierte Investitionen auf Standortebene [Mrd. €]
BAU	2,360	43,8	7,6	0	36,2	1,84
Elektrifizierung	0,492	33,3	26,0	7,3	0	5,64
Wasserstoff	0,492	38,7	14,5	24,2	0	3,76
Hybrid	0,492	36,8	24,8	12,0	0	6,15
CCS	0,344	35,5	23,1	2,2	10,2	6,11

Hinweis: Die Investitionswerte beziehen sich auf kumulierte Investitionen auf Standortebe-
und -transportinfrastruktur sowie externe CO₂-Transportnetze und geologische Speicher für die Flachglasindustrie sind nicht vollständig berücksichtigt.

Der Vergleich in **Tabelle 5** verdeutlicht ein zentrales Ergebnis der Modellierung: Die drei gesamtindustriellen Transformationspfade erreichen im Jahr 2045 dasselbe Niveau an verbleibenden CO₂-Emissionen, nutzen hierfür jedoch grundlegend unterschiedliche Technologie- und Energiesysteme. Die Auswahl eines Transformationspfads kann daher nicht allein anhand der Emissionen im Zieljahr erfolgen. Energiebedarf, Infrastrukturbedarf, technologische Reife, Investitionsanforderungen und Betriebskosten sind gleichermaßen relevant.

Die Entwicklung der jährlichen Emissionen über den Modellierungszeitraum verdeutlicht diesen Zusammenhang. Elektrifizierungs-, Wasserstoff- und Hybridpfad reduzieren die Emissionen bis 2045 auf 0,492 Mio. t CO₂/a und damit um 86,5 % gegenüber 2024. Die verbleibenden Emissionen sind überwie-

gend prozessbedingt und resultieren aus der Zersetzung karbonathaltiger Rohstoffe. Der CCS-Pfad reduziert die Restemissionen weiter auf 0,344 Mio. t CO₂/a, da sowohl verbrennungsbedingte als auch prozessbedingte CO₂-Emissionen aus den CCS-ausgerüsteten Flachglaswannen abgeschieden werden können. Da CCS entsprechend den angenommenen Wannenrevisionszyklen jedoch erst ab 2040 eingeführt wird, ist der Beitrag zur kumulierten Emissionsminderung über den gesamten Betrachtungszeitraum geringer, als es der Vergleich der Endwerte für 2045 zunächst vermuten lässt.

Die Pfade unterscheiden sich darüber hinaus deutlich in ihren Anforderungen an das zukünftige Energiesystem (vgl. **Tabelle 6**). Die Elektrifizierung führt zum höchsten Strombedarf, während der Wasserstoffpfad mit Abstand die größten Mengen an Was-

serstoff erfordert. Der Hybridpfad verteilt den Energiebedarf auf Strom und Wasserstoff und reduziert damit die Abhängigkeit von einem einzelnen zukünftigen Energieträger. Gleichzeitig müssen beide Infrastrukturen parallel verfügbar sein. Der CCS-Pfad führt eine zusätzliche Infrastrukturdimension ein: Neben Strom und der weiterhin bestehenden

Erdgasversorgung benötigen die entsprechenden Flachglas Standorte Zugang zu CO₂-Aufbereitung, -Transport und dauerhafter geologischer Speicherung.

Tabelle 6 Zentrale Merkmale und Infrastrukturbedarfe der Transformationspfade

Pfad	Zentrales Merkmal des Energiesystems	Wichtigste Infrastrukturvoraussetzung	Wesentlicher Vorteil	Zentrale Umsetzungs-herausforderung
Elektrifizierung	Starke Verlagerung zum Energieträger Strom	Netzausbau und höhere Anschlusskapazitäten an den Standorten	Niedrigster Endenergiebedarf	Netzkapazitäten, kontinuierliche Stromversorgung und wettbewerbsfähige Strompreise
Wasserstoff	Weitgehende Substitution von Erdgas durch Wasserstoff	Wasserstofferzeugung, Transport und regionale Verteilung	Niedrigster CAPEX der drei Transformationspfade	Verfügbarkeit und Kosten ausreichender Wasserstoffmengen
Hybrid	Kombination aus Strom und Wasserstoff	Paralleler Ausbau von Strom- und Wasserstoffinfrastruktur	Diversifizierung über zwei Energieträger	Abhängigkeit von der parallelen Entwicklung zweier Infrastruktursysteme
CCS	Oxy-Fuel-Flachglas Produktion mit CO ₂ -Abscheidung	CO ₂ -Aufbereitung, Transport und dauerhafte geologische Speicherung	Niedrigste Restemissionen	CO ₂ -Infrastruktur, Betriebskosten für Abscheidung und fortgesetzter Erdgasbedarf
BAU	Fortführung konventioneller Wärentechnologien	Bestehende Erdgas- und Strominfrastruktur	Geringster Transformationsaufwand	Hohe Restemissionen und fortgesetzte Abhängigkeit von fossilen Energieträgern

Die Investitionsschätzungen sind als Modellergebnisse und nicht als vollständige Abbildung aller systemweiten Transformationskosten zu verstehen. Berücksichtigt werden der Ersatz oder Umbau der Schmelzwannen sowie die technologiespezifische Infrastruktur innerhalb der Produktionsstandorte bis zur Schnittstelle zur externen Strom-, Wasserstoff- oder CO₂-Infrastruktur. Externe Übertragungs- und Verteilnetze, Wasserstofferzeugung und -transport sowie CO₂-Transportnetze und geologi-

sche Speicher sind nicht abgebildet. Die tatsächlichen Investitionsbedarfe einzelner Standorte können daher höher ausfallen.

Der Investitionsvergleich in **Tabelle 7** verdeutlicht die erheblichen Unterschiede zwischen den Pfaden. Der BAU-Pfad erfordert bis 2045 kumulierte Basisinvestitionen in Höhe von 1,84 Mrd. €. Unter den drei Transformationspfaden weist der Wasserstoffpfad mit 3,76 Mrd. € den niedrigsten kumulierten Investitionsbedarf auf Standortebe-
auf, gefolgt

vom Elektrifizierungspfad mit 5,64 Mrd. € und dem Hybridpfad mit 6,15 Mrd. €. Der CCS-Pfad erreicht 6,11 Mrd. €. Vergleichbare Investitionen auf Standorte-bene bedeuten jedoch nicht zwangsläufig, dass die Gesamtsystemkosten ähnlich ausfallen. Der Wasserstoffpfad ist insbesondere von zukünftigen Wasserstoffpreisen und dem Aufbau der entsprechenden Infrastruktur abhängig, der Elektrifizierungspfad von Strompreisen und Netzkapazitäten, der Hybridpfad vom parallelen Ausbau zweier Energieinfrastrukturen und der CCS-Pfad zusätzlich von Erdgas- und Sauerstoffkosten, den Betriebskosten der CO₂-Abscheidung sowie den Transport- und Speicherkosten.

Tabelle 7 Kumulierte Investitionsanforderungen auf Standorte-bene bis 2045

Pfad	Kumulierte Investitionen bis 2045	Zusätzliche Investitionen gegenüber Referenz / BAU
BAU	1.84 Mrd. €	–
Wasserstoff	3.76 Mrd. €	1.92 Mrd. €
Elektrifizierung	5.64 Mrd. €	3.80 Mrd. €
CCS	6.11 Mrd. €	4.27 Mrd. €
Hybrid	6.15 Mrd. €	4.31 Mrd. €

Die Betriebskosten sind genauso relevant wie die anfänglichen Investitionen. Eine technisch mögliche Transformation ist nur dann langfristig wirtschaftlich tragfähig, wenn die daraus resultierenden Energie- und Carbon-Management-Kosten eine wettbewerbsfähige Glasproduktion über die gesamte Lebensdauer der Anlagen ermöglichen. Für die Glasindustrie bedeutet dies insbesondere, dass CO₂-armer Strom und Wasserstoff hinsichtlich der Energiekosten mit einer erdgasbasierten Produktion konkurrenzfähig werden müssen oder das verbleibende Kostendifferenzen durch verlässliche politische Instrumente ausgeglichen werden.

Über alle Transformationspfade hinweg werden die verbleibenden Emissionen im Jahr 2045 überwiegend durch prozessbedingte CO₂-Emissionen beim Einsatz karbonathaltiger Rohstoffe bestimmt. Auch

eine weitgehende Dekarbonisierung der Prozessenergie kann die Emissionen daher nicht vollständig beseitigen. Ein höherer Scherbeneinsatz sowie alternative Rohstoffe bleiben wichtige ergänzende Maßnahmen. Ihr Potenzial wird jedoch durch die Verfügbarkeit, die Sortierqualität, Reinheitsanforderungen sowie produktspezifische und regulatorische Anforderungen begrenzt. Dies gilt insbesondere für Flachglas und technisches Glas. CO₂-Abscheidung und -Speicherung sollten daher als ergänzende Optionen für verbleibende Prozessemissionen diskutiert werden, sofern dies technisch, wirtschaftlich und infrastrukturell umsetzbar ist.

Der Pfadvergleich zeigt zudem, dass die wesentlichen Transformationshemmnisse nicht ausschließlich technischer Natur sind. Die Elektrifizierung erfordert ausreichende Netzkapazitäten, höhere Anschlussleistungen an den Standorten sowie eine zuverlässige Stromversorgung zu international wettbewerbsfähigen Preisen. Die wasserstoffbasierte Transformation hängt entscheidend von der zukünftigen Wasserstofferzeugung, den Importen sowie den Transport- und Verteilstrukturen ab. Hybridkonzepte setzen voraus, dass beide Systeme parallel entwickelt werden. CCS erfordert zusätzlich die CO₂-Abscheidung, den Transport und die Speicherung.

Auch der technologische Reifegrad ist von zentraler Bedeutung. Die Existenz einer Technologie im Pilot- oder Demonstrationsmaßstab bedeutet nicht automatisch, dass sie bereits für sämtliche Glasprodukte und Wannengrößen kommerziell verfügbar ist. Dies ist insbesondere bei der großskaligen Flachglas Produktion relevant, bei der Wannengröße, Prozessstabilität und hohe Qualitätsanforderungen den technisch erreichbaren Elektrifizierungsgrad weiterhin begrenzen. Die Roadmap verknüpft die Technologieeinführung daher mit realistischen Wannenrevisionszyklen und differenziert zwischen den einzelnen Glassegmenten, statt eine einheitliche Transformation der gesamten Branche anzunehmen.

Planungssicherheit für Strom-, Wasserstoff- und CO₂-Infrastruktur, wettbewerbsfähige Energiepreise, langfristig verlässliche Förderinstrumente,

Unterstützung bei zusätzlichen Betriebskosten sowie tragfähige Lösungen für verbleibende Prozessemissionen sind daher zentrale Voraussetzungen für die Umsetzung. Diese Rahmenbedingungen müssen nicht nur grundsätzlich vorhanden sein, sondern auch am jeweiligen Produktionsstandort genau zu dem Zeitpunkt verfügbar sein, an dem eine Wanne zur Revision beziehungsweise zum Neubau ansteht.

Die Roadmap unterstreicht darüber hinaus die Bedeutung eines wirksamen Schutzes vor Carbon Leakage. Die finale Regelung des europäischen CO₂-Grenzausgleichsmechanismus (CBAM) trat am 1. Januar 2026 in Kraft. Glasprodukte gehören nicht zu den vom Mechanismus unmittelbar erfassten Sektoren. CBAM bietet der Glasindustrie insbesondere in der derzeitigen Ausgestaltung keinen direkten Schutz vor Carbon Leakage. Zusätzliche Schutzmechanismen bleiben erforderlich, damit die Transformation nicht zu einer Verlagerung der Produktion in Regionen mit niedrigeren Energiepreisen oder schwächeren Klimaschutzanforderungen führt, ohne die globalen Emissionen tatsächlich zu senken. Angesichts der zuletzt verschlechterten wirtschaftlichen Lage der deutschen Glasindustrie und der hohen Sensitivität der zukünftigen CO₂-armen Produktion gegenüber Strom-, Wasserstoff-, CO₂- und Infrastrukturkosten ist dieses Risiko besonders relevant.

Aus den Ergebnissen der Roadmap ergeben sich konkrete Handlungsschwerpunkte für Politik und Glasindustrie, die in **Tabelle 8** zusammengefasst sind. Für die Politik gehören hierzu insbesondere die Beschleunigung des Ausbaus der Stromnetz- und Wasserstoffinfrastruktur, die Verbesserung der wirtschaftlichen Rahmenbedingungen für die industrielle Elektrifizierung, langfristig stabile Förderinstrumente, die Begrenzung zusätzlicher Betriebskostenrisiken, die Stärkung der Kreislaufwirtschaft und der Rohstoffstrategien innerhalb ihrer technischen Grenzen, die Entwicklung einer realistischen Carbon-Management-Regulierung sowie ein wirksamer Carbon-Leakage-Schutz bei Ein- und Ausfuhren.

Auf Seiten der Glasindustrie liegen zentrale Handlungsschwerpunkte in der Abstimmung der Transformationsplanung mit den Wannenrevisionszyklen, der Entwicklung standortspezifischer Transformationsstrategien, der strategischen Berücksichtigung von Stromversorgung und Netzkapazitäten, der selektiven Bewertung des Wasserstoffeinsatzes sowie dem gezielten Einsatz hybrider Konzepte bei technologischen oder infrastrukturellen Unsicherheiten. Darüber hinaus sollten nachgelagerte Prozesse in die standortspezifische Transformationsplanung einbezogen und frühzeitig Strategien zum Umgang mit verbleibenden Prozessemissionen entwickelt werden. Über alle Pfade hinweg gilt eine zentrale wirtschaftliche Voraussetzung: Eine sich selbst tragende Transformation kann nur stattfinden, wenn die Energiekosten für CO₂-armen Strom und Wasserstoff gegenüber einer erdgasbasierten Produktion wettbewerbsfähig werden oder politische Instrumente die verbleibenden Kostendifferenzen verlässlich ausgleichen. Wettbewerbsfähige Preise für CO₂-arme Energie sowie die Unterstützung von Investitionen und zusätzlichen Betriebskosten sind damit wesentliche Voraussetzungen für eine industrielle Dekarbonisierung ohne Wettbewerbsfähigkeitseinbußen. Insgesamt zeigt die aktualisierte Roadmap, dass eine weitgehende Dekarbonisierung der deutschen Glasindustrie bis 2045 technisch grundsätzlich möglich ist, jedoch nicht automatisch erfolgen wird. Die Pfade unterscheiden sich erheblich hinsichtlich des Strom- und Wasserstoffbedarfs, der Investitionsanforderungen, der Infrastrukturabhängigkeiten und der Umsetzungsrisiken. Elektrifizierung gewinnt über alle Glassegmente hinweg an Bedeutung. Wasserstoff wird zunehmend selektiv dort eingesetzt, wo eine vollständige Elektrifizierung technisch nicht möglich ist. Hybridlösungen ermöglichen die Kombination unterschiedlicher Technologien und können Infrastruktur- und Technologierisiken verteilen.

CCS stellt für die großskalige Flachglas Produktion eine zusätzliche Option zur Reduktion der verbleibenden Prozess- und Verbrennungsemissionen dar.

Die entscheidende Herausforderung besteht daher nicht allein darin, mögliche Technologien zu identifizieren. Entscheidend ist vielmehr, die industriellen, infrastrukturellen, wirtschaftlichen und regulatorischen Rahmenbedingungen zu schaffen, unter

denen Unternehmen diese Technologien zu den relevanten Wannenrevisionszeitpunkten tatsächlich einsetzen können und gleichzeitig eine international wettbewerbsfähige Glasproduktion in Deutschland erhalten bleibt.

Tabelle 8 Zentrale Handlungsfelder für die Politik und die deutsche Glasindustrie

Politik	Glasindustrie
Ausbau von Stromnetzen und Standortanschlüssen beschleunigen	Transformationsplanung mit Wannenrevisionszyklen abstimmen
Aufbau von Wasserstofferzeugung, Transport und regionaler Verteilung unterstützen	Standortspezifische Transformationsstrategien entwickeln
Verlässliche CO ₂ -Transport- und Speicherinfrastruktur für industrielle CCS-Anwendungen entwickeln	Stromversorgung und Netzkapazität als strategische Standortfaktoren behandeln
Wirtschaftliche Rahmenbedingungen für industrielle Elektrifizierung verbessern	Wasserstoff entsprechend technischer Anforderungen und lokaler Infrastruktur selektiv einsetzen
Langfristig stabile Investitionsförderinstrumente bereitstellen	Hybridkonzepte gezielt bei technologischer oder infrastruktureller Unsicherheit einsetzen
Zusätzliche Betriebskostenbelastungen während der Transformation adressieren	Nachgelagerte und unterstützende Prozesse in die Transformationsplanung integrieren
Kreislaufwirtschaft und Rohstoffstrategien innerhalb ihrer technischen Grenzen stärken	Frühzeitig Strategien für verbleibende Prozessemissionen entwickeln

Introduction and Objectives of the Roadmap

The glass industry plays a crucial role in various value chains. It is a significant source of industrial greenhouse gas emissions. Glass products are vital for packaging, construction, pharmaceuticals, mobility, electronics, and many other applications. Transforming this sector matters not only for climate policy but also for industrial resilience, supply security, and technological competitiveness.

Decarbonizing glass production, however, presents significant challenges. This stems from reliance on continuous, high-temperature processes; the need for long furnace lifetimes; strict product quality requirements; and, often, intense international competition. Furthermore, the industry is highly heterogeneous, with subsectors that vary in furnace concepts, energy intensity, product requirements, and market structures. Recent analyses of the German glass industry reveal that individual sites and products have highly specific production needs. As a result, it is essential to distinguish between flat glass, hollow glass, and technical glass. A realistic decarbonization roadmap must reflect these differences rather than assume a one-size-fits-all approach.

Accordingly, the roadmap offers a differentiated, practical perspective on transforming the German glass industry. It aims to support decision-makers across industry, policy, public administration, and research by identifying relevant transition routes, key implementation barriers, and priority areas for action.

This report updates the initial glass industry roadmap published in 2022. It incorporates developments since then, including technical advancements, changing policy conditions, infrastructure planning, and new insights from companies and experts. It pursues four main objectives:

1. It offers a transparent overview of the current state of the German glass industry, including its

structure, emissions profile, and key transformation challenges.

2. It assesses and compares various decarbonization pathways: a BAU Pathway, an Electrification Pathway, a Hydrogen-based Pathway, and a Hybrid Pathway for the glass industry as a whole. It further examines the Hybrid Pathway at the segment level for hollow glass, flat glass, and technical glass. It also analyses a separate Carbon Capture and Storage (CCS) Pathway for flat-glass production, evaluating on-site CO₂ capture and transport for permanent geological storage.
3. It analyses how economic, infrastructural, and political factors influence investment decisions and the pace of transformation.
4. It provides concrete recommendations for the glass industry and decision-makers to enhance planning security and support the necessary implementation of transformation measures.

The report emphasises the sector's heterogeneity by covering hollow glass, flat glass, and technical glass. Together with other glass, these segments accounted for approximately 95% of Germany's glass production by tonnage in 2024, excluding stone wool from the reference total. This figure reflects the share of the glass segments considered, not the proportion of individual production sites represented in the model. These segments differ significantly in production structures, plant sizes, operating conditions, and technological options. The roadmap does not provide comprehensive statements on glass-fibre production, flat-glass finishing, or other downstream processes outside the scope of the BV Glas member companies covered in the report. This distinction matters when comparing with broader production or emissions statistics. Segment-specific differences, including the physical locations of production sites, influence both feasible decarbonisation pathways and the correspond-

ing financial implications. Thus, the roadmap integrates an industry-wide perspective with segment- and site-specific analyses.

Transforming melting furnaces is central to the pathway modelling. However, the site-level energy balances also include energy consumption associated with feeders, forming and annealing lehrs. These processes are therefore already reflected in the modelled final energy demand. Other auxiliary processes, particularly compressed-air generation and drives, are not explicitly modelled.

Site-specific transformation planning must therefore also consider the remaining fossil-fuel use, additional electricity requirements and infrastructure needs associated with auxiliary processes outside the explicit model scope.

Many of these processes are already predominantly electricity-based. Nevertheless, practical transformation planning must address remaining fossil-fuel use, future electricity demand, and necessary site-level infrastructure.

The report is based on extensive empirical data. The report draws on information from the glass industry through a dedicated online tool, which formed the basis for modelling individual site transformation pathways. It is supplemented by a literature review,

expert interviews, stakeholder feedback, and a review of relevant research and development activities. The analysis also examined patent activity to identify broader innovation trends relevant to the sector's transformation. Based on this foundation, the team developed transformation scenarios reflecting different strategic focuses, enabling comparison of potential pathways through 2045. Effective transformation planning in the glass industry must combine technical analysis with detailed information on furnace types, production conditions, site-level execution constraints, and the required external energy infrastructure—or a continuous, resilient energy supply. The definitive EU CBAM regime has been in force since 1 January 2026, but it does not currently include glass products in its sectoral scope. The question of effective carbon-leakage protection therefore remains highly relevant for the sector.

This roadmap should therefore be understood as both an analytical update and a practical orientation framework. It does not provide a single blueprint for the industry's future or an individual transformation plan for each production site. Instead, it delivers a structured basis for decision-making amid technological uncertainty, infrastructure dependence, and long-term industrial investment cycles.

1 Overview of the German Glass Industry

The German glass industry is a strategically important basic-materials sector whose relevance extends far beyond its direct economic output. Germany is Europe's largest glass producer and a leading producer worldwide. The sector is deeply embedded in European and international value chains, and supplies essential products for construction, packaging, pharmaceuticals, mobility, infrastructure, consumer goods, and a wide range of technical applications. Hollow glass is indispensable for food and beverage packaging as well as for pharmaceutical and medical applications. Flat glass plays a central role in buildings, energy-efficient renovation, mobility, and infrastructure. Technical glass serves a broad range of specialized applications, including electronics, optics, and other technologically demanding products. Maintaining a competitive domestic and European production base matters not only for industrial value creation but also for supply security, crisis preparedness, and the resilience of key value chains. At the same time, glass products drive transformation in downstream sectors. High-performance glazing can reduce buildings' energy demand; glass is essential to solar-energy technologies; and hollow glass is a key material for circular packaging systems. The sector's strategic relevance must therefore be assessed from two perspectives: the glass industry is a hard-to-abate basic-materials industry, but its products also enable decarbonization and resource efficiency in other parts of the economy. However, the sector's economic situation has become increasingly challenging since 2023. Production volumes have stabilized at a lower level, but broader economic pressures have persisted. These developments illustrate the difficult starting point for the transformation. The German glass industry is expected to invest in low-carbon technologies, new infrastructure, and site-level conversion measures even as turnover declines, employment falls, imports rise, and competitive pressure remains strong. Decarbonization must therefore be

designed to preserve industrial production in Germany and Europe. A transformation that merely shifts production to regions with lower energy costs or weaker carbon regulation would not necessarily reduce global emissions. Still, it could weaken resilient supply chains and strategic industrial capacity.⁴⁻⁶

1.1 The Role of the Glass Industry in Industrial Value Chains

The glass industry's importance extends beyond its direct emissions profile because its products support decarbonization in downstream sectors, such as the building sector. British Glass highlights that flat glass enables high-efficiency glazing in buildings, glass fibers are necessary for wind turbine blades and lightweight vehicles, and hollow glass plays a major role in the circular economy. These arguments are not UK-specific; they also apply to glass's role in Europe as an enabling material for low-carbon buildings, circular packaging, and industrial applications. The sector must be understood both as a hard-to-abate industry and as a supplier of products that support broader decarbonization elsewhere in the economy.^{2,7,8}

At the same time, the industry's trade exposure means that domestic decarbonisation cannot be analysed independently of competitiveness. The annual reports of BV Glas^{1,3} underline the importance of imports and exports across glass product groups, and the British Glass Association (British Glass)² explicitly warns that climate policy should not decarbonize the sector through deindustrialization or carbon leakage. The same strategic concern is evident in the current German policy context, where recent policy documents link industrial decarbonisation to competitiveness, energy costs, and industrial location conditions.⁹

1.2 Current Challenges for the Glass Industry

1.2.1 Industrial Challenges

From an industrial perspective, glass production relies on continuous processes throughout a furnace's full lifetime and tolerates little interruption. Glass production must run continuously to avoid damaging the furnace and to preserve thermal equilibrium and product quality, as changes in operating conditions typically lead to production scrap. Because of thermal inertia and melt residence times, process adjustments often take days or even weeks to stabilise. This means that process transformation is closely tied to major reinvestment windows and involves substantial operational risk. The industrial challenge is intensified because many technological decisions have long lifecycles. Furnace life typically ranges from 10 to 20 years, depending on furnace type and site-specific conditions. In this roadmap, however, we assess transformation timing on a site-specific basis, using the relevant rebuild or cold repair windows of the plants included in the analysis. As a result, missing a rebuild or conversion window at the end of a furnace's life will lock in technology and carbon for many years.^{2,5}

1.2.2 Technical Challenges

Technically, the main challenge is maintaining very high, highly stable process temperatures while strictly controlling melting and refining conditions. Natural gas remains the dominant energy source in glass production. At the same time, electricity plays a relevant but smaller role because it is more expensive than other energy carriers, though it is available in most regions of Germany. German process-chain and sector studies identify hybrid furnaces, full electrification, oxy-fuel concepts, cullet and batch pre-heating, and waste heat recovery as central technological options for reducing emissions. However, process-related emissions remain a structural challenge. These emissions arise from the decomposition of carbonate-based raw materials and there-

fore cannot be eliminated by decarbonising the energy supply alone. International sector strategies explicitly emphasise that process emissions are harder to reduce than combustion emissions and will require higher cullet shares, alternative or decarbonised raw materials, and CCS or CCU to achieve net-zero emissions.^{2,5}

1.2.3 Economic Challenges

Economically, the sector faces a difficult mix of high energy intensity, major investment requirements, and sustained market weakness. The downturn became clear in 2023, when total production fell by 13.1% and turnover by 3.1%, while employment initially remained broadly stable at 55,000. The latest BV Glas industry overview shows that the pressure has persisted. Total production was 6.66 million tonnes (Mt) in 2024 and 6.60 Mt in 2025, a further 0.9% decline. Over the same period, sector turnover decreased from €11.26 billion to €10.71 billion. Employment fell from 53,600 to 50,960, while establishments with at least 20 employees fell from 382 to 360. Imports rose by 6.5%, and the trade surplus fell by 30.4% to €1.10 billion. The industry is therefore expected to undertake capital-intensive decarbonisation under strained market conditions rather than during a phase of strong cyclical growth.^{1,6}

This roadmap highlights energy pricing and electrification economics as a key dimension of the transformation challenge. The scenario analysis indicates that decarbonisation in the glass industry is likely to rely heavily on all-electric and hybrid melting furnaces, both of which significantly increase plant-level electricity demand. At the same time, the economic viability of these pathways depends not only on furnace technology itself but also on electricity market design and grid fee structures. In particular, losing baseload-related electricity price advantages would substantially weaken the business case for hybrid and, especially, electric furnaces.⁵

1.2.4 Decarbonisation Challenges

Decarbonising the glass industry is a system-level process shaped by asset structures, process constraints, market exposure, infrastructure availability, and public policy.^{4,5,10} Process emissions make the glass industry hard to abate. The glass industry cannot solve residual process emissions on its own.

1.2.5 Societal and Regulatory Challenges

Regulatory and societal conditions strongly shape the glass industry's transformation. The analysis shows that decarbonisation pathways in the glass sector are shaped not only by technology and plant economics, but also by the policy framework that underpins investment decisions. In particular, the competitiveness of decarbonised glass production depends on whether the broader framework supports infrastructure rollout, technology transition, and continuous access to low-carbon energy carriers. This is especially relevant for a sector that relies on uninterrupted production and therefore cannot easily adapt to uncertain energy supply conditions. This is consistent with broader sector assessments BY dena⁴ and BV Glas¹¹ both of which underline the importance of supportive framework conditions for industrial transformation.

Recent policy developments further show that the need for transformation support is increasingly being translated into concrete funding instruments. In Germany, the Federal Funding for Industry and Climate Protection (BIK) (<https://www.klimaschutz-industrie.de/foerderung>), coordinated by the Competence Centre for Climate Protection in Energy-Intensive Industries (KEI), explicitly supports industrial decarbonisation projects, including electrification, fuel switching to renewable hydrogen, and, where relevant, CCS/CCU-related investments.

This confirms a central finding of this roadmap: the transformation challenge is not only recognised at the strategic level but is increasingly reflected in the design of dedicated support mechanisms. At the same time, funding alone is not sufficient. Long-

term investment decisions in the glass industry still depend on planning certainty regarding infrastructure availability, electricity prices, and future operating conditions.^{12,13}

Overall, the overview of the German glass industry highlights the roadmap's central conclusion: the sector's decarbonisation challenge is not defined by a single bottleneck but by the interplay of industrial structure, process constraints, infrastructure dependence, market pressures, and policy design. This is why the following chapters integrate industry structure, site-level data, current R&D, and scenario analysis into a single integrated roadmap.

2 Current Situation and Need for Action

The German glass industry is transitioning to climate neutrality under increasingly difficult conditions. On the one hand, the sector is expected to align with the 2045 greenhouse-gas neutrality objective. On the other hand, it must do so while running continuous high-temperature processes, maintaining product quality, and staying competitive in international markets. This tension between climate ambition and industrial viability is not new, but it has intensified since the first roadmap was published in 2022. Recent industry data, comparative sector roadmaps, infrastructure developments, and policy changes point to the same conclusion: the need for action has grown, while implementation conditions have become more complex. In addition, geopolitical instability and renewed volatility in international energy markets have reinforced the importance of both energy security and cost resilience for energy-intensive industrial production. The central challenge is therefore no longer only to identify technically conceivable decarbonisation technologies. The decisive question is whether these technologies can be implemented at industrial scale, at the required furnace capacities and product qualities, and under infrastructure and cost conditions that keep glass production competitive in Germany. The following sections summarise the main developments since 2022 and the resulting economic, political, infrastructural, and technological need for action.^{2,14,15}

2.1 Developments since the first Glass Roadmap published in 2022

Since the publication of the first roadmap for the German Glass Industry in 2022, several framework conditions have changed, become more concrete, or been regulated.

First, the infrastructure debate has advanced significantly. In Germany, the Federal Network Agency of

Germany (Bundesnetzagentur) approved the Hydrogen Core Network on October 22, 2024. According to the Bundesnetzagentur, the approved network comprises 9,040 km, 60% of which will be converted from existing natural gas pipelines, with expected investment costs of €18.9 billion. This matters for the glass industry because hydrogen-based pathways depend not on hydrogen as an abstract future option, but on whether specific sites will be connected to a functioning network in time.¹⁶

For the glass industry, however, national backbone approval does not automatically imply hydrogen availability at individual production sites. The decisive questions are the geographical distance between a glass-production site and the core network, the need for regional connecting infrastructure, the timing of the respective network section, and the availability and price of hydrogen once the connection becomes operational. Consequently, this roadmap's infrastructure assessment distinguishes between the existence of the national Hydrogen Core Network and actual site-level accessibility (see Fehler! Verweisquelle konnte nicht gefunden werden.).

Second, the carbon management policy framework has advanced substantially. The legal situation has moved beyond the 2024 Carbon Management Strategy.¹⁷ And the associated legislative proposal. The amendment adopted in November 2025 changed the legal framework into the Carbon Dioxide Storage and Transport Act (KSpTG)¹⁸. The KSpTG now provides the legal framework for planning and approving CO₂ pipelines and permanent geological CO₂ storage. Subject to statutory exceptions, the construction and operation of CO₂ pipelines and the European Container Glass Federation storage facilities are explicitly classified as being in the overriding public interest.

This marks an important shift for the glass industry because electrification or hydrogen alone cannot eliminate process-related emissions from carbonate-based raw materials. At the same time, CCS should not be understood exclusively as a technology for process emissions. Where a furnace continues to use a carbon-containing fuel, a capture system can, in principle, address both fuel-related and process-related CO₂ in the flue gas. By contrast, electrification removes the corresponding combustion-related CO₂ but does not eliminate the CO₂ released from carbonate decomposition. The relative attractiveness of these routes therefore depends on the furnace concept, capture scale, energy requirements, infrastructure access, future gas-network availability, and achievable economies of scale. International glass-sector assessments similarly distinguish fuel switching from the need to address residual process emissions.² At the federal level, the government's current communication highlights sectors such as cement, lime, parts of the basic chemicals industry, and waste incineration. A similar pattern appears at the regional level. Baden-Württemberg¹⁹ places the strongest emphasis on cement and lime, although it explicitly notes that technically unavoidable emissions can also arise in the glass industry. By contrast, the North Rhine-Westphalia strategy²⁰ foregrounds steel, aluminium, cement, and plastics, while describing process emissions as occurring particularly in cement and lime. For the glass industry, this implies a dual challenge: carbon management is becoming more relevant in legal and infrastructure terms, but the sector remains less visible in policy prioritisation than other hard-to-abate industries, despite also facing structurally persistent process emissions.

Third, the European carbon policy environment has entered a more decisive phase. However, the current CBAM product scope includes cement, iron and steel, aluminium, fertilisers, electricity, and hydrogen. The German glass industry therefore currently receives no direct product-level carbon-leakage protection through CBAM. Unfortunately, the current regulation is still leaving many open questions and would not be useful in the export competition.

This distinction is important: the gradual CBAM-related phase-out of free allocation concerns the sectors and goods covered by the mechanism and should not be presented as if glass itself were currently covered. For the glass industry, the broader issue remains whether it can bear rising carbon and transformation costs without shifting production and investment toward regions with lower energy or climate-policy costs.^{21–23}

Fourth, support instruments for industrial decarbonisation have become more tangible. In 2024, the German government launched the Federal Funding for Industry and Climate Protection (Bundesförderung Industrie und Klimaschutz, BIK), and BMWK explicitly highlighted that CCU and CCS investment support had been newly integrated in line with the Carbon Management Strategy. At the same time, project-level information in the glass sector shows that funding discussions for energy-intensive industries now directly address electrification and hydrogen use. This means that the transition is no longer shaped only by strategic targets, but increasingly by specific funding windows and investment support mechanisms.^{17,24}

Finally, the market situation has deteriorated. The downturn became clear in 2023, when total production fell by 13.1% and turnover by 3.1%. BV Glas reported that the industry had entered a difficult economic phase. Since then, production volumes have stabilised at a lower level, but the broader economic pressure has persisted. In 2025, total glass production fell by another 0.9%. Sector turnover fell 4.8% from €11.26 billion in 2024 to €10.71 billion in 2025, while employment fell 4.9% to 51,000. Foreign-trade developments reinforce this picture. Export value remained almost unchanged at €8.76 billion in 2025, while imports rose 6.5% to €7.66 billion. Consequently, the trade surplus declined by 30.4%, from €1.56 billion in 2024 to €1.10 billion in 2025. At the same time, the export ratio rose to 58.3%, reflecting both the sector's continued international orientation and its exposure to international competition.^{1,6,11}

The combination of declining turnover, falling employment, rising imports, and a shrinking trade surplus is particularly important for the transformation this roadmap considers. Investment in low-carbon furnaces and site infrastructure is not happening during a period of strong industrial growth, but under already weakened competitiveness. Additional CAPEX and, in particular, additional OPEX can therefore directly influence whether Germany rebuilds and transforms a furnace, reinvests conventionally, postpones, or ultimately does not replace it.

At the time of writing, renewed geopolitical tensions in the Middle East have added further uncertainty. The conflict has substantially disrupted international energy markets and once again highlighted industrial production's vulnerability to fossil-fuel price shocks. This reinforces the need to strengthen industrial energy supply resilience while ensuring the transition remains economically viable.²⁵

2.2 Economic and Political Framework Conditions

The interaction between economic and political framework conditions strongly shapes the glass industry's capacity for transformation. From an economic perspective, the key factors are electricity and fuel prices, expected hydrogen costs, carbon pricing, financing conditions, and the ability to pass through additional decarbonisation costs in competitive product markets. From a policy perspective, support instrument design, electricity pricing, network charges, emissions trading, and infrastructure planning are central. Because future operating costs are highly uncertain, OPEX support will likely matter more than pure CAPEX funding. The challenge is that these dimensions are interlinked and determine whether an available decarbonisation technology is currently investable at plant level.^{2,15}

Current German industry evidence shows that these pressures are already material. The 2025 economic briefing of BV Glas highlighted substantial declines in turnover and production across major glass segments. Industrial natural gas prices have doubled in

recent years, creating a difficult market environment and adding to the sector's broader strain. Decarbonisation in the glass industry is capital-intensive and must be financed under already difficult conditions, before the full cost of transformation is even added. We have recently seen conventional reinvestments at the end of furnace life postponed or rejected, without considering decarbonised processes.¹⁴

Electricity costs are particularly critical. Recent analysis indicates that decarbonisation in the glass industry will likely be driven above all by increased electrification through all-electric or hybrid melting furnaces, both of which significantly increase energy efficiency but also site-level electricity demand. At the same time, the sector offers only limited short-term flexibility because processes must run continuously, and changes in operating conditions can lead to production scrap. In addition, competition is increasing among data centres, battery storage plants, and other industrial facilities aiming to decarbonize by using electricity, given available grid capacity. Electrification therefore cannot be analysed separately from electricity market design, network charges, increased network capacities and the availability of reliable baseload supply.⁵

Comparative sector roadmaps from other countries point in the same direction. British Glass identifies electricity costs, network upgrades, infrastructure access, and long-term competitiveness as high-priority policy issues for reaching net zero, and explicitly calls for support that covers not only CAPEX but also additional OPEX. The French sectoral transition plan for the glass industry likewise emphasizes that the sector must decarbonize while remaining competitive and identifies electrification as a core lever of transformation. These comparisons reinforce the conclusion that the German case is not unusual: high-temperature glass decarbonisation is fundamentally dependent on energy-system and industrial-policy conditions, not only on technology maturity.^{2,15}

From a political perspective, planning security emerges as a key requirement. Glass furnaces are long-lived assets, and major technological shifts typically occur in rebuild cycles rather than through annual optimization decisions. This matters because the glass industry is not only energy-intensive, but also part of the broader industrial base, supplying essential downstream sectors such as construction, packaging, pharmaceuticals, mobility, and technical applications, while also contributing to regional value creation and employment. If the timing of electricity grid expansion, hydrogen rollout, carbon pricing, or public support remains uncertain, firms face a strong incentive to postpone deep decarbonisation investments. This is why current framework conditions matter not only for cost levels, but also for predictability and implementation timing.^{2,16,22}

2.3 Technological Developments

The technological landscape of glass decarbonisation has become substantially more concrete since 2022, but no single universal technology has emerged. The main options remain electrification, hydrogen-based combustion, hybrid furnace concepts, circularity and raw-material measures, and carbon capture for emissions that remain in the furnace exhaust gas. Their applicability differs considerably between hollow glass, flat glass, and technical glass, depending on furnace size, product requirements, glass chemistry, site infrastructure, and rebuild timing. The strong need for this segment-specific assessment is also reflected in current German industry studies, which emphasise that individual site and glass-product requirements differ substantially.^{2,4,15}

The patent analysis in chapter 8.1.5 supports this assessment and was conducted as part of the roadmap update. The review of international patent activity between 2000 and 2025 indicates that innovation efforts are increasingly concentrated on electrified and hybrid melting concepts, while further patent activity can be observed in furnace design, hydrogen- and oxygen-related combustion

technologies, exhaust-gas treatment, process optimization, energy-efficiency measures, recycling-related innovations, and CO₂-reduction solutions. The patent landscape therefore reflects a broadening portfolio of decarbonisation technologies rather than the emergence of one single dominant solution. At the same time, patent activity must not be interpreted as direct evidence of technological maturity or commercial availability. Patents indicate areas of innovation and strategic interest, but industrial applicability still depends on furnace scale, product requirements, operating conditions, and successful demonstration under real production conditions.

The analysis identifies **electrification** as a central technological option for reducing combustion-related emissions from glass melting. All-electric furnaces, electric boosting, and highly electrified hybrid concepts can substantially reduce or eliminate direct fossil-fuel use while also increasing furnace-level energy efficiency. At the same time, the assessment shows that full electrification is not currently assumed to be technically transferable to all glass products and furnace sizes. Applicability differs substantially between hollow glass, flat glass, and technical glass and depends in particular on furnace capacity, glass composition, refining requirements, product quality, and available electricity infrastructure. This assessment aligns with current German and international sector studies, which also identify electrification as a major decarbonisation option while emphasizing remaining scale and application limitations. Furnace capacity remains a key constraint. Current all-electric furnaces are predominantly used at comparatively small production scales.

The 2025 assessment of energy flexibility in the German glass industry reports capacities below 180 t/day for current all-electric furnaces and identifies 300–400 t/day as a development target. The dena sector guide similarly reports a current technical limit of 200 t/day, with exceptional applications reaching 300 t/day. By contrast, conventional combustion-based furnaces can exceed 1,000 t/day.

This difference matters for large-scale Flat-glass production and explains why complete electrification cannot yet be treated as equally mature across all glass segments.

Further development is also required in furnace design and operation. Relevant technical questions include melt convection beneath the batch blanket, refining at high throughput, electrode design and positioning, electrical current density, local overheating, short-circuit flows, electrode corrosion, and the interaction between electrode operation and refractory materials. These factors affect both achievable furnace capacity and furnace lifetime. The roadmap therefore treats technical maturity not merely as the availability of an electrically heated furnace concept, but as the ability to achieve the required production volume, product quality, and campaign length under industrial operating conditions. Furnace lifetime is particularly relevant from an investment perspective. The current German assessment reports typical lifetimes of 5–8 years for all-electric furnaces compared with 12–20 years for conventional furnaces, depending on the glass type. Shorter furnace campaigns mean more frequent rebuilds and can therefore increase cumulative investment requirements, even when an individual electric furnace offers lower energy consumption.

The limitations are most pronounced for large-scale flat glass. The roadmap therefore does not assume complete electrification of all flat-glass production within the Electrification Pathway. Instead, highly electrified hybrid concepts remain necessary where full-electric operation is not considered technically feasible within the modelled period. Current sector assessments reflect the same general limitation, identifying all-electric concepts primarily for hollow glass and technical glass while treating large-scale Flat-glass electrification as substantially more challenging. Electrification is therefore not only a furnace-technology question but also an infrastructure question. Increasing the electrical share of glass melting requires substantially higher grid-connec-

tion capacities, reliable continuous electricity supply, and sufficient internal electrical infrastructure at the production site. Because glass melting is a continuous process with limited short-term flexibility, electrified furnaces generally cannot respond to electricity-market fluctuations as flexibly as other industrial loads. The flexibility assessment results for the German glass industry support this finding and show that increasing electrification raises electricity demand while fundamental limits to short-term process flexibility remain.^{2,4,15}

The analysis identifies **hydrogen** as a technically possible substitute for natural gas in glass melting, but also as a pathway subject to considerable technological, infrastructural, and economic uncertainty. Hydrogen combustion can maintain a combustion-based furnace principle and may therefore offer advantages in applications for which complete electrification remains technically difficult. However, its implementation cannot be understood as a simple one-to-one replacement for natural gas. Existing investigations indicate that regenerative glass furnaces can in principle be converted to hydrogen combustion with appropriate modifications. The assessment nevertheless identifies several technical issues that must be considered in such a conversion. These include adapting burners and regenerators to the changed combustion and flue-gas characteristics, higher flame temperatures, potentially increased NO_x formation, higher water-vapor concentrations, changes in the glass melt's water content, and increased NaOH evaporation. The latter may increase corrosion risks for the furnace superstructure and regenerators. Similar findings are also reported in the dena sector guide and underline that refractory behavior and furnace lifetime under hydrogen operation remain important issues for industrial application. The relevance of these challenges differs between glass segments. The technological assessment indicates that hydrogen combustion is currently more readily applicable to Hollow glass than to large-scale Float-glass production. This reinforces the need for segment-specific pathway assumptions rather than a uniform hydrogen transition across the entire industry. Infrastructure

availability represents a separate constraint. The approval of the German Hydrogen Core Network has significantly increased national planning certainty, but the backbone network does not automatically ensure hydrogen availability at individual glass-production sites. Key factors include a site's location relative to the network, the availability of regional connections, the commissioning date of the relevant network section, and the volume and price of hydrogen ultimately available to industrial consumers. The roadmap therefore evaluates hydrogen infrastructure at the site level rather than treating core-network approval as equivalent to guaranteed supply. On-site hydrogen production through electrolysis represents a possible alternative where pipeline access is unavailable, but it does not remove the infrastructure challenge. Large-scale hydrogen demand would require correspondingly large electrolyser capacities, plus substantial additional electricity supply, grid connection capacity, water supply, storage, and space. Therefore, the availability and economic viability of sufficiently large electrolysers must be assessed as part of the overall site-specific energy concept, rather than assumed as a universally available substitute for network hydrogen. Consequently, the roadmap treats hydrogen as a potentially important but comparatively infrastructure-dependent decarbonisation option. This interpretation aligns with other European glass-sector assessments, which likewise identify hydrogen as technically relevant while emphasizing uncertainty about supply infrastructure, costs, furnace adaptation, and large-scale commercial application.^{2,16}

Hybrid concepts have gained importance because of these uncertainties. Importantly, “hybrid” does not refer to one fixed technology or one fixed combination of energy carriers. A hybrid furnace combines electrical heating with a gaseous energy carrier. Still, this gaseous component may be natural gas during an initial transition phase, hydrogen once suitable supply becomes available, or, in selected applications, a biogenic fuel. The technological and strategic rationale for hybridisation therefore differs by furnace and site. An electricity–natural-gas

hybrid configuration can increase the electrical share before sufficient grid capacity or a technically mature full electric furnace is available. It can also reduce fossil-fuel consumption without immediately replacing the entire combustion-based heating concept. An electricity–hydrogen hybrid can retain a combustion component where full electrification remains constrained by furnace size, glass quality, or process requirements while progressively replacing fossil natural gas with a lower-carbon energy carrier. Hybridisation can therefore reduce the risk of committing a long-lived furnace to a single energy carrier whose future infrastructure, price, or technical applicability remains uncertain. For this reason, the Hybrid Pathway should primarily be understood as a bridging and risk-management strategy. It enables a gradual transition from today's predominantly natural-gas-based furnace stock toward higher electrical shares while maintaining the option to substitute the remaining gaseous energy input at a later stage. In applications where complete electrification remains technically constrained, hybrid furnace concepts may still play a longer-term role beyond the transition period. Comparable sector strategies likewise highlight hybrid furnaces' ability to increase the electrical share over the furnace lifetime and subsequently replace the gaseous component with hydrogen. At the same time, the ability to use more than one energy carrier should not be confused with unrestricted short-term energy flexibility. The analysis shows that changes in furnace operating conditions affect melt convection, temperature distribution, and product quality and therefore cannot generally be implemented instantaneously.

The 2025 German flexibility assessment indicates that adjustments may take hours to days, that poorly adjusted operating points can cause one or more days of off-specification production, and that higher electrical shares make flexible operation increasingly difficult. Frequent changes in the energy-carrier mix may also negatively affect furnace lifetime. Hybrid concepts are therefore valuable primarily because they provide technological and stra-

tegic flexibility over the furnace campaign—not because they allow the furnace to switch freely between electricity and gas in response to short-term market signals.^{2,5,15}

The analysis also considers biogenic gaseous fuels as a possible complementary option, particularly for existing furnace systems and hybrid configurations. Biomethane has combustion properties broadly compatible with existing natural-gas-based furnace technology and can, in principle, be supplied through existing gas infrastructure. This can reduce fossil CO₂ emissions without requiring the same extent of furnace redesign as a switch to electricity or hydrogen. The dena sector guide identifies biomethane as a potentially relevant short-term option for existing glass furnaces. However, its potential for the overall transformation is limited by sustainable resource availability, price, and competition with other sectors. The roadmap therefore does not treat biogas or biomethane as an unlimited replacement for natural gas across the German glass industry. Instead, it represents a selective option that may be relevant for individual sites or during transitional periods. Comparable assessments in the British glass industry reach a similar conclusion: biofuels can offer a relatively rapid fuel-switching option but face limitations in availability, cost, sustainability, storage, and competition for biomass resources.^{2,4}

Technological developments also extend beyond energy carriers. Comparative sector studies explicitly treat increased cullet use, alternative or decarbonated raw materials, and process-emission reduction strategies as essential components of deep decarbonisation pathways. Increased cullet use reduces both melting energy demand and process emissions because cullet avoids decomposing part of the virgin carbonate raw materials. At the same time, the remaining process emissions mean calcined raw materials, alternative feedstocks, and potentially CCS/CCU must be considered for decarbonisation.^{2,4,15}

CCS and CCU have become more relevant in policy and scenario discussions because process-related emissions persist. CCS and CCU are increasingly relevant for transforming the glass industry, particularly because no single technological option can fully reduce both energy-related and process-related emissions.

With the 2025 amendment to the KSpTG, Germany has established a much more concrete legal framework for CO₂ transport and permanent geological storage. The technological assessment therefore treats CCS, electrification, hydrogen, raw-material measures, and CCU as potentially complementary, not mutually exclusive, options. Electrification and hydrogen can reduce or eliminate fuel-related emissions. In contrast, process-related CO₂ from carbonate decomposition remains and requires additional measures such as increased cullet use, alternative raw materials, CCS, or potentially CCU. Where carbon-containing fuels continue to be used, CCS can in principle capture both fuel-related and process-related CO₂ from the furnace exhaust gas. This may provide economies of scale compared with capturing the smaller residual process-emission stream after extensive fuel switching. At the same time, the long-term viability of such a pathway depends on the availability of gaseous-energy infrastructure, since a future reduction or repurposing of natural-gas networks could change the relative attractiveness of continued combustion combined with CCS. Comparable glass-sector assessments likewise identify carbon capture as a relevant option for emissions remaining after other decarbonisation measures, particularly for process-related CO₂.^{2,17,18,26}

Overall, the technological assessment shows that the transformation is best understood as a portfolio of options rather than a competition for one universally superior furnace technology. Electrification offers the greatest potential to directly eliminate combustion emissions where furnace scale and product requirements allow it. Hydrogen can retain combustion-based melting where full electrification remains difficult but introduces additional technical

and infrastructure dependencies. Hybrid furnaces provide an important bridging and risk-management option between these routes. Raw-material measures reduce the residual process-emission burden, while CCS offers a potential route to address remaining CO₂ emissions, particularly in Flat

glass. The appropriate combination therefore depends on the individual glass segment, furnace size, site infrastructure, rebuild cycle, and long-term energy and CO₂-management conditions.

3 Update of the Transformation Pathways

The updated transformation pathways assume the German glass industry will not decarbonize through a single universal technology. Instead, the available evidence points to a portfolio of possible pathways whose suitability depends on subsector, furnace type, infrastructure access, product-quality requirements, and reinvestment timing. European sector studies support this conclusion: electrification, hydrogen, hybridization, circularity, and, in some cases, carbon management must be understood as interacting elements rather than mutually exclusive alternatives.

This chapter therefore does not define one deterministic future for the glass industry, but updates and compares plausible transformation pathways under current technological, infrastructural, and policy conditions. In this sense, the scenarios are analytical tools: they let us compare the implications of different technological emphases for energy demand, emissions, infrastructure dependence, and investment timing. This approach aligns closely with comparative sectoral work that structures decarbonisation into multiple pathways rather than a single target technology.

3.1 Methodological Approach

The methodological approach for updating the transformation pathways combines the site-level status assessment with broader assumptions on technological development, infrastructure availability, and policy framework conditions. The scenarios therefore are not based solely on idealised technical potential, but on a practice-oriented assessment of what may become feasible under actual industrial conditions. This includes the structure and age of the installed furnace stock, the continuous nature of glass production, the limited short-term operational flexibility of the processes, and the expected timing of electricity and hydrogen infrastructure.

Recent sector evidence strongly reflects these constraints, emphasizing that glass production processes must operate continuously and that deep decarbonisation through electrification or hybridization is associated with a significant increase in plant-level electricity demand.

Beyond site-level data and scenario assumptions, the pathway assessment is grounded in a process-oriented understanding of glass manufacturing. This includes the technical requirements of melting, refining, conditioning, forming, and annealing, as well as the need to maintain stable thermal conditions and consistent product quality throughout continuous operation. The analysis therefore assesses furnace technologies not only on nominal energy balances, but also on process stability, product-specific constraints, and the operational feasibility of technology shifts under real industrial conditions.

Methodologically, the scenarios assume that glass furnaces are replaced or fundamentally modernized only at discrete intervals. Rebuild windows therefore become decisive moments for transformation. Existing sector strategies explicitly identify long furnace lifetimes and rebuild timing as key strategic constraints and present hybrid furnace concepts as a way to preserve technological optionality under uncertain infrastructure development. The updated pathways in this roadmap follow the same logic: technology choices are not treated as continuously reversible decisions, but as long-lived investment decisions made under uncertainty.

When interpreting changes in furnace stock, the analysis distinguishes between technological conversion and the withdrawal of structural capacity. A decline in conventional furnace capacity does not automatically imply replacement by a low-carbon technology; depending on the site-specific context,

it may also reflect the closure of individual furnaces or the discontinuation of production at a given site. In addition, the scenario design does not assume one uniform transition logic for the entire sector. Instead, it reflects the glass industry's heterogeneity across subsectors, furnace types, product requirements, and site-specific boundary conditions. The roadmap therefore distinguishes between electrification, hydrogen-based, and hybrid furnace pathways, while treating additional levers such as increased cullet use, alternative raw materials, energy efficiency, and optional CCS/CCU as complementary elements of transformation.

3.2 Baseline and Core Assumptions

Baseline and Reference Year

The updated transformation pathways in this roadmap are based on a 2024 baseline reflecting the current state of the German glass industry. Unlike the previous roadmap, which relied on earlier reference data, this update uses 2024 as the analytical starting point to reflect the sector's current technological configuration, recent market developments, and the most recent site-level information available through the roadmap process.

Choosing 2024 as the reference year ensures that the transformation pathways are assessed against current industrial reality rather than pre-crisis conditions from earlier years. In particular, the 2024 baseline reflects the sector's current structure in terms of production technologies, energy use, emissions, infrastructure conditions, and the current economic situation. This is especially important because the glass industry has faced significant market pressure, shifting energy prices, and intensified decarbonisation debates since the first roadmap was prepared.

The baseline comes from the site-level assessment conducted during the roadmap update. It therefore reflects the current stock of relevant glass plants, furnaces, and associated production characteristics included in the model framework. Where complete site-specific information was not available, we used

additional assumptions, extrapolations, and plausibility checks to construct a consistent analytical baseline. As a result, the model-based baseline used in the roadmap may differ slightly from official statistical aggregates. These differences are accepted where necessary to preserve internal consistency across the scenario analysis.

For the updated roadmap, the relevant glass segments considered here amount to 3.79 Mt of hollow glass, 1.79 Mt of flat glass, and 0.29 Mt of technical and utility glass in 2024. These values serve as the starting point for the subsequent scenario analysis.

Energy Efficiency Assumptions

The updated transformation pathways assume incremental technical progress will continue through 2045. This applies to both the existing plant stock and newly introduced decarbonisation technologies. Efficiency improvements may result from better process control, waste heat recovery, improvements in cross-cutting technologies such as motors and compressors, operational learning, and the gradual technical optimization of new furnace concepts. For the scenario analysis, we assume a uniform annual efficiency improvement of 0.3% for both the current plant stock and newly introduced decarbonisation technologies after market entry. This assumption reflects gradual technical progress rather than disruptive breakthroughs. It does not eliminate the need for structural decarbonisation, but it influences the magnitude of future energy demand in all scenarios.¹⁰

Decarbonisation of Auxiliary Process Steps

Although melting remains the main source of energy demand and direct emissions, additional process steps such as feeders, forming and annealing also consume energy and contribute to the sector's overall emissions profile. The energy demand of these processes is already included in the site-level energy balances and is therefore reflected in the modelled final energy demand. Other auxiliary processes, particularly compressed-air generation and drives, are not explicitly modelled.

In the updated roadmap, we assume that the non-melting process steps included in the model decarbonise progressively, primarily through electrification and the increased use of low-carbon electricity. We do not develop separate alternative decarbonisation pathways for these steps, as the main analytical focus remains on melting technologies and their infrastructure implications. Accordingly, we assume that fossil fuel use in the included downstream processes is phased out by 2045. Site-specific transformation planning must address additional energy requirements and decarbonisation measures for auxiliary processes outside the explicit model scope.

Infrastructure Assumptions

Infrastructure availability is a central condition for all transformation pathways considered in this roadmap. Low-carbon production routes can reduce emissions only if the required energy carriers and, where relevant, carbon-management systems are available at the right sites, in sufficient quantities, and at the right time. Infrastructure assumptions therefore play a decisive role in the design and plausibility of the scenarios.

For electricity, the updated roadmap assumes that decarbonising the glass industry will substantially increase plant-level electricity demand, especially in the Electrification and Hybrid Pathways. German glass plants already use electricity to produce different glass types, although in most cases it is not the main energy source for melting. As a result, the sites considered in this roadmap generally already have an electricity connection and a small backup power system. However, most glass plants are currently connected to the medium-voltage grid, which can still supply current electricity demand. The usual connection capacity of a glass plant in Germany ranges from 3 to 15 MW, typically supplied at 10 to 20 kV.

Existing site connections are often sufficient for current production structures, but in many cases, they are unlikely to be adequate for large-scale electric melting or highly electrified hybrid furnaces. The

transition from fossil-fuel-fired furnaces to electrically heated melting furnaces would substantially increase both peak power demand and total electricity consumption at the respective sites compared with current conditions. To meet this additional demand, the existing connection capacities and the current integration of most plants into the medium-voltage grid are unlikely to be sufficient. In many cases, future decarbonisation will therefore require connection to the 110 kV high-voltage grid. Consequently, the condition of the electricity grid and individual plants' distance to the high-voltage network are key determinants of the feasibility and timing of furnace electrification across the geographically dispersed German glass industry. These factors therefore critically determine the speed and site-specific feasibility of electrification pathways. This assumption aligns with both sector evidence of rising electricity demand and the broader debate on grid readiness for energy-intensive industries. To assess the future deployment of decarbonisation measures, we supplement the current electricity grid with expansion measures already confirmed by the Federal Network Agency. This lets us estimate the expected timing of sufficient electricity connections for individual sites and, on this basis, the earliest plausible point at which glass furnaces could switch to electric melting technologies.

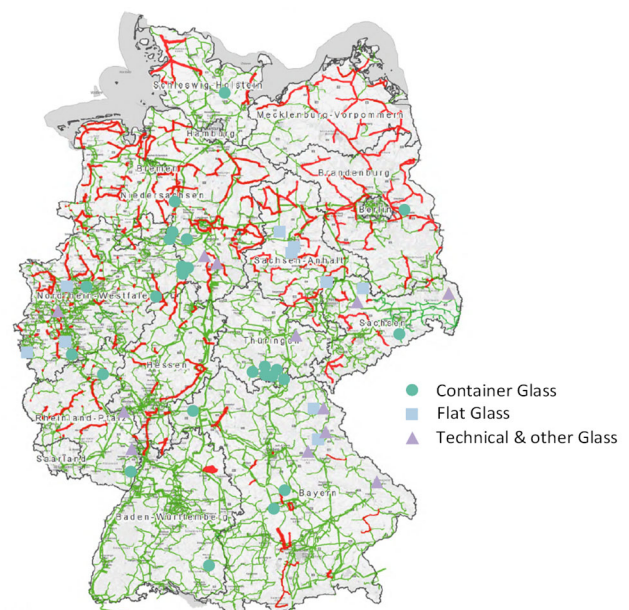
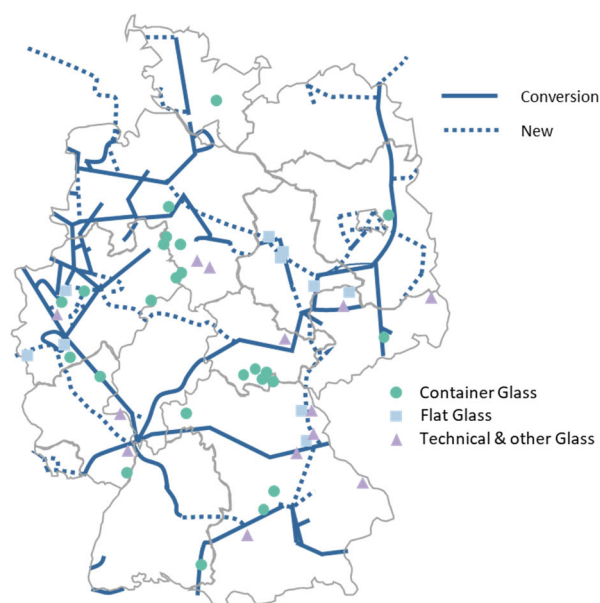


Figure 1 High-voltage grid (110 kV) in Germany (2021), extended by the locations of German glass plants (red lines = congestion areas).^{10,16,27–29}

2030



2050

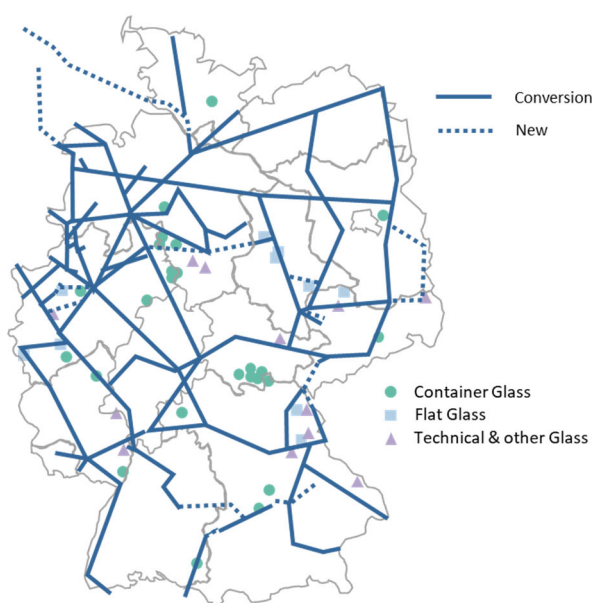


Figure 2 Planned hydrogen network in Germany for 2030 (left) and 2050 (right).^{32,33}

For hydrogen, the updated roadmap assumes it will be a realistic option only at sites that can connect to future transport infrastructure. Hydrogen is not treated as a universally available energy carrier, and the scenarios do not assume that all sites will have equal access at the same time, as shown in **Figure 2**.

Instead, hydrogen-based transformation depends on the regional rollout of network infrastructure and whether industrial sites can connect within relevant investment windows. The Hydrogen Core Network approved in October 2024 provides an important planning basis, but it does not imply simultaneous or uniform hydrogen availability for all glass plants. The approved network comprises 9,040 km of pipelines, 60% of which are conversions of existing natural gas pipelines, with stepwise commissioning planned up to 2032 and expected total investment costs of €18.9 billion.^{2,16,28–32}

Where CCS/CCU is considered as a complementary option, the updated roadmap also assumes that carbon capture is only meaningful where a broader CO₂ transport and storage chain may realistically emerge (see **Figure 3**). This means plant-level capture is not assessed in isolation, but alongside the likely availability of transport routes and storage or utilization options. Because Germany only recently

created a more concrete legal framework for CO₂ transport and storage, and because physical infrastructure will require considerable lead times, CCS/CCU remains a site-specific, long-term option rather than a universally available short-term solution.^{33–37}

Energy and Carbon Price Assumptions

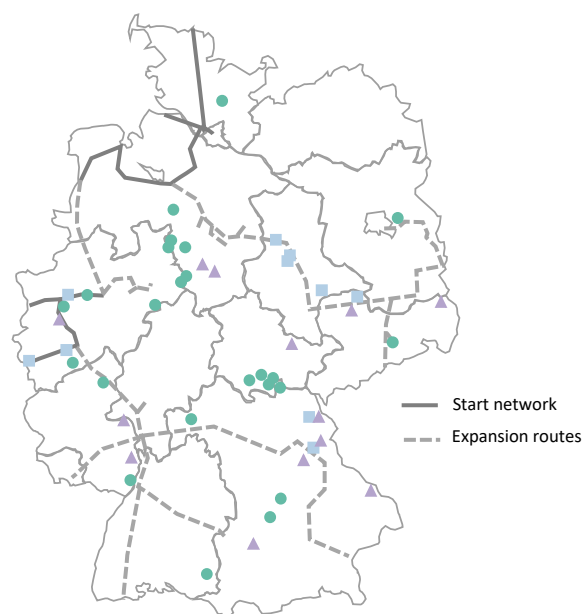


Figure 3 Planned CO₂ pipeline network in Germany in 2032.

The updated transformation pathways also depend on assumptions regarding future energy and carbon

prices. These assumptions strongly influence the economic comparison of electrification, hydrogen-based, hybrid, and fossil reference technologies. They do not aim to predict future markets precisely, but to provide a transparent, internally consistent basis for comparing the cost implications of different pathways.

For electricity and natural gas, the roadmap applies band-specific end-user prices for industrial consumers in Germany rather than relying solely on wholesale or commodity price assumptions. This is consistent with the methodology used by the German Environment Agency for the 2025 greenhouse gas projections. These end-user prices include procurement and sales costs, plus taxes, levies, and network charges. They are therefore more suitable for plant-level techno-economic comparison than wholesale prices alone.²⁷

For electricity in particular, the updated roadmap assumes price levels and price design will remain critical factors for decarbonisation. Because electrification and hybridization significantly increase plant-level electricity demand, the economic attractiveness of these pathways depends not only on wholesale electricity prices, but also on grid charges, industrial tariff structures, and the treatment of continuous industrial loads. This makes electricity price assumptions particularly important for the Electrification Pathway's feasibility. Current European industry evidence also underlines that electricity prices for industrial consumers remain a central barrier to wider deployment of electric and hybrid glass melting.³⁸

For natural gas, the updated roadmap treats gas prices primarily as a reference for comparison. Gas remains relevant because it defines the economic benchmark from which low-carbon alternatives must diverge. At the same time, recent years have shown that gas price development is highly uncertain and can be strongly affected by geopolitical events and market disruptions. Gas price assumptions should therefore be understood as scenario

assumptions rather than stable long-term expectations.^{38–40}

For hydrogen, the central question is not only whether hydrogen becomes physically available, but whether it becomes available at a price compatible with industrial competitiveness. The updated roadmap therefore treats hydrogen cost as a key uncertainty variable when comparing scenarios. Even if hydrogen infrastructure expands, high hydrogen costs may delay or limit practical uptake in the glass sector. Current European industry sources consistently underline that hydrogen remains promising in principle, but constrained by both cost and availability.^{32,39}

Finally, the pathways include assumptions about future CO₂ prices. Rising CO₂ prices increase the economic pressure on fossil-based production and improve the relative position of low-carbon technologies. For this reason, carbon price assumptions remain a key part of the analytical framework. In the updated roadmap, they should be treated as structured scenario assumptions that reflect continued tightening of carbon policy rather than as exact forecasts. This logic is reinforced by the transition from the CBAM transitional phase to the definitive regime from 1 January 2026 onward.

Development of energy and CO₂ allowance prices

In addition to direct energy costs, the cost of CO₂ allowances required to use fossil energy carriers represents a significant share of glass's specific production costs. Deploying decarbonisation technologies reduces demand for fossil fuels and, consequently, the need for CO₂ allowances. As CO₂ prices rise, the cost gap between fossil-based and low-carbon or renewable energy carriers narrows.

For fossil energy carriers, installations covered by the EU ETS also do not include the cost of CO₂ allowances in reported end-user prices; companies bear this cost separately. In this roadmap, energy carrier prices and CO₂ costs are therefore presented sepa-

rately to transparently illustrate the effect of emissions trading on the economics of fossil and renewable technology options **Figure 4**.

For hydrogen, no official end-user price is available for 2024; the value used for that year is therefore an extrapolated assumption based on the available projection data.²⁷

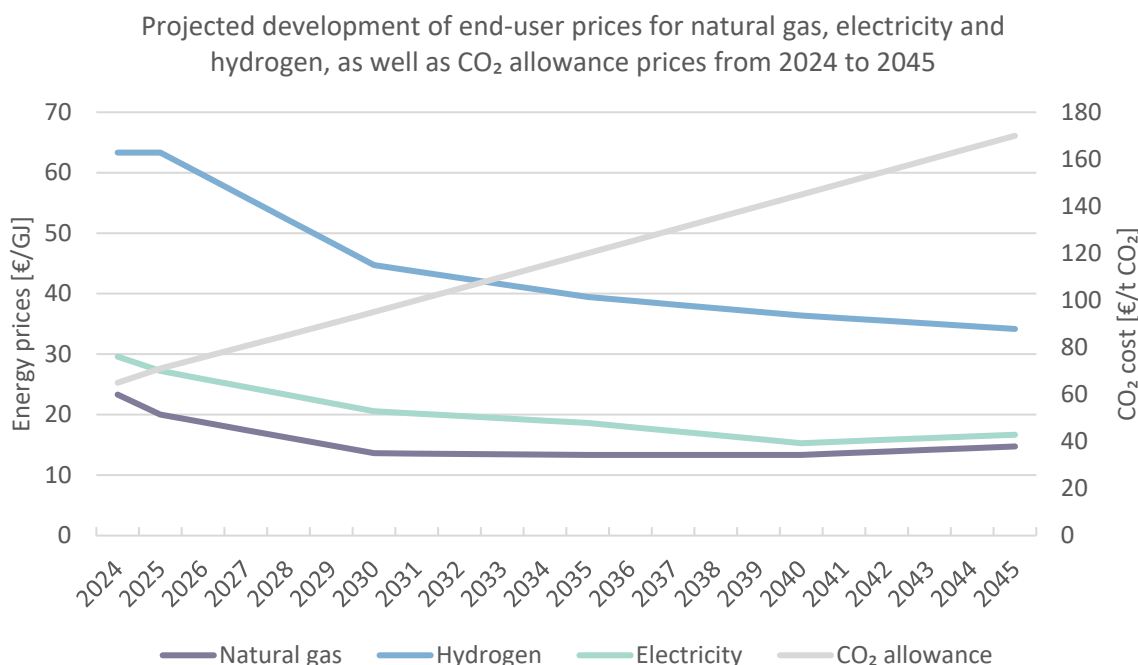


Figure 4 Projected development of end-user prices for natural gas, electricity and hydrogen, as well as CO₂ allowance prices from 2024 to 2045.^{31,40,41}

3.2.1 Optional Integration of CCS/CCU

An updated transformation assessment must also address the potential role of carbon capture and storage or utilization (CCS/CCU). Process-related emissions from carbonate-based raw materials remain significant even if electrification, hydrogen use, and efficiency improvements strongly reduce energy-related emissions. Comparative sector strategies therefore treat carbon capture primarily as a complementary option for residual emissions rather than a substitute for decarbonising process energy.

Germany's policy and regulatory framework for carbon management has become more concrete in recent years. The amendment to the German Carbon Dioxide Storage Act entered into force on 28 November 2025, expanding the legal basis for larger-scale CO₂ capture, transport, and storage. This is relevant for the glass industry because residual process emissions cannot be eliminated through fuel

switching alone. At the same time, legal enablement does not imply immediate practical availability. Developing transport infrastructure, storage capacity, and viable utilization routes requires substantial lead times and must align with site-specific industrial investment cycles. In this roadmap, CCS/CCU is therefore not treated as a universal standalone pathway for the entire glass industry. Instead, it is assessed as an optional complementary sub-pathway for eligible large flat-glass production sites from 2040 onwards. These sites matter because large float-glass furnaces operate continuously, generate substantial, concentrated CO₂ streams, and face demanding requirements for process stability, product quality, and furnace scale. Where full electrification or other low-carbon alternatives remain technically, economically, or infrastructurally constrained, carbon capture may offer an additional option to reduce otherwise difficult-to-avoid emissions. The CCS/CCU sub-pathway does not replace prior efforts to reduce emissions

through energy-efficiency improvements, electrification, hybrid furnace concepts, hydrogen use, increased cullet shares, or alternative raw materials. Instead, it complements these measures by addressing residual fuel-related and process-related emissions contained in the flue-gas stream of eligible furnaces. Its practical relevance depends on the availability of suitable capture technologies, access to CO₂ pipeline infrastructure, viable storage or utilization routes, legal conditions, social acceptance, and economic feasibility.

CCS/CCU therefore expands the technological solution space without implying that carbon capture will become the preferred option for all glass-production sites. Its role remains conditional, site-specific, and closely linked to the timely development of CO₂ transport and storage infrastructure.

3.2.2 Improvement of Circularity

Increasing cullet content constitutes an important no-regret option for reducing both process-related and energy-related emissions in glass manufacturing. In this assessment, higher cullet shares yield measurable additional reductions in process CO₂ emissions and melting energy demand across all major subsectors. This is consistent with the broader sector literature, which shows that cullet use lowers melting energy demand and avoids carbonate-related process emissions from virgin raw materials. British Glass reports that every additional 10 % points of cullet can save 2.5% of furnace energy. At the same time, German sector guidance states that a 10-percentage-point increase in cullet content can reduce energy consumption by 3% and CO₂ emissions by 5%.^{2,4,10}

At the same time, material availability and quality requirements limit how much cullet content can increase. Further increases in cullet use require higher collection and recycling rates, improved sorting and processing infrastructure, and a sufficient supply of high-quality, application-specific cullet. Sector evidence explicitly points to shortages of good-quality cullet for glass manufacturing, including flat-glass cullet for float-glass production. These

constraints are particularly relevant for flat glass, where product-quality requirements and process conditions further restrict feasible cullet uptake. Consequently, increasing cullet content should be a central lever for circularity in the sector's decarbonisation strategy. However, its practical mitigation potential depends on successfully expanding closed-loop recycling systems and reliably supplying high-quality secondary raw materials.^{2,4,10}

4 Transformation Pathways

The following sections analyse four pathways for transforming the glass industry. They represent the broad range of possible developments and therefore describe the possible solution space.

4.1 BAU Pathway

The Reference Pathway describes the expected development of the glass industry in Germany without a dedicated and focused shift toward low-carbon melting technologies. It therefore represents a business-as-usual (BAU) pathway under prevailing technological, economic, and regulatory framework conditions. Operators largely retain and replace existing furnace concepts within normal rebuild cycles, without a systematic transition to low-carbon melting technologies.

Accordingly, the BAU Pathway serves as a benchmark against which the transformation pathways can be assessed. This pathway's changes are driven not primarily by structural technological change, but by limited efficiency improvements, the progressive decarbonisation of electricity supply, rising carbon prices, and the temporary or permanent shutdown of individual furnaces or production sites over time.

Production capacities by technology.

Table 5 presents the updated BAU pathway, as the German glass industry's technological structure remains largely unchanged over the modelling horizon. Conventional regenerative furnaces fuelled by fossil fuels remain dominant. At the same time, non-conventional technologies already in the current furnace stock remain in operation, including full-electric furnaces, individual hybrid furnace concepts, oxy-fuel furnaces, and hybrid electro-plus-oxy-hydrogen configurations. However, the reference pathway assumes no systematic, market-wide diffusion of new decarbonisation technologies. **Table 9** shows the distribution and development of installed melting furnaces across the considered glass sectors for 2024, 2035, and 2045.

The main adjustment in installed production capacity occurs in the first transition phase from 2024 to 2035, particularly between 2024 and 2025. This change reflects individual furnace or plant closures rather than a structural transformation of the sector. After these initial economically driven adjustments, installed production capacity remains broadly stable over the modelling horizon. Total installed production capacity amounts to 5.8 Mt/year in 2024, declines to 5.77 Mt/year in 2025, and then remains at this level until 2045.

Table 9 Expected development of the number of installed melting furnaces by sector in the BAU Pathway

Technology	2024				2035				2045			
Conventional	53	13	46	112	46	10	46	102	46	10	46	102
Fully electric	2	-	5	7	2	-	5	7	2	-	5	7
Hybrid (CH ₄)	1	-	-	1	1	-	-	1	1	-	-	1
Hybrid (H ₂)	-	-	-	-	-	-	-	-	-	-	-	-
Super-hybrid (CH ₄)	-	-	-	-	-	-	-	-	-	-	-	-
Super-hybrid (H ₂)	-	-	-	-	-	-	-	-	-	-	-	-
Hollow glass	Flat glass				Technical glass				Total			

Energy consumption

Because the reference pathway does not shift broadly toward alternative energy carriers, natural gas remains the dominant energy source for melting and downstream processes throughout the period. Electricity remains the second-largest energy carrier, while hydrogen and biogas play no material role in the pathway. **Figure 5** shows the development of final energy demand by energy carrier in the Reference Pathway.

Natural-gas consumption declines from 41.09 PJ in 2024 to 36.15 PJ in 2045, a 12% reduction. Electricity consumption decreases from 8.11 PJ to 7.64 PJ, a 6% reduction. Consequently, total final energy demand decreases from 49.20 PJ in 2024 to 43.79 PJ in 2045. These changes result not primarily from active technological transformation, but from initial adjustments in installed capacity, modest efficiency improvements, and the continuation of the existing production structure.

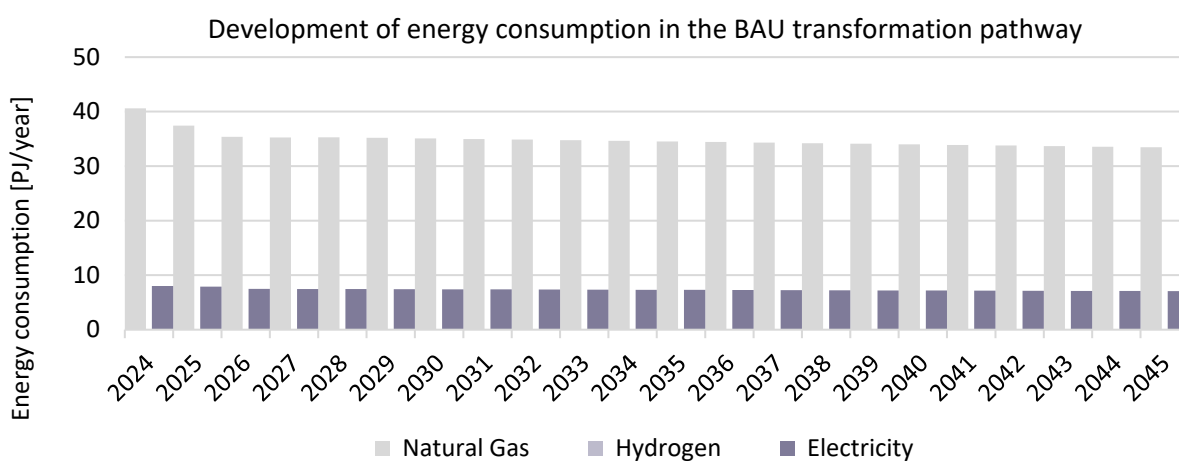


Figure 5 Development of energy consumption in the BAU Pathway

CO₂ emissions

Since conventional furnace technologies remain dominant in the Reference Pathway, direct energy-related CO₂ emissions decline only moderately over time (see **Figure 6**). Total CO₂ emissions decrease from 3.64 Mt CO₂/year in 2024 to 2.35 Mt CO₂/year in 2045. This reduction is mainly attributable to two factors. First, the assumed closure of selected furnaces reduces production volumes, lowering both fuel-related and process-related emissions. Second, the power sector's gradual decarbonisation substantially reduces indirect emissions from electricity consumption.

Direct emissions decrease from 2.84 Mt CO₂/year in 2024 to 2.35 Mt CO₂/year in 2045. Indirect emissions decline more strongly, from 807,800 t

CO₂/year in 2024 to zero by 2045. This reduction results from the assumed gradual decline in the electricity-grid emission factor, which the model assumes reaches 0 t CO₂/MWh in 2045. Process-related emissions decline only slightly, from 567,600 t CO₂/year in 2024 to 493,700 t CO₂/year in 2045.

Accordingly, the emission reduction achieved in the Reference Pathway is not driven by a fundamental transformation of furnace technologies. Instead, it largely results from declining production volumes and the applied decarbonisation of the electricity supply.

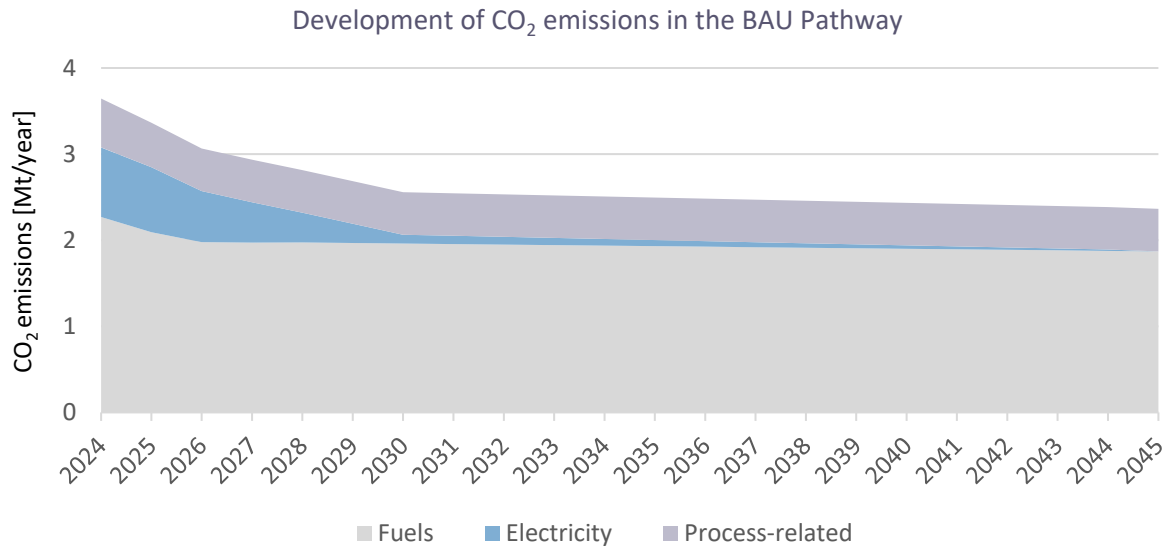


Figure 6 Development of CO₂ emissions in the BAU Pathway

Investments

The investments required in the Reference Pathway are limited to routine furnace refurbishment, replacing existing assets where continued operation is assumed, and maintaining the existing production system. Because no major technology transition is implemented, annual investment needs remain comparatively moderate.

million. Cumulative investment reaches €1.84 billion by 2045.

These expenditures represent baseline reinvestments needed to sustain current production capacities, not additional transformation-related investments.

Figure 7 shows annual and cumulative investment requirements. They range from about €30.8 million to €147.6 million per year. Average annual investment over the period 2024–2045 amounts to €83

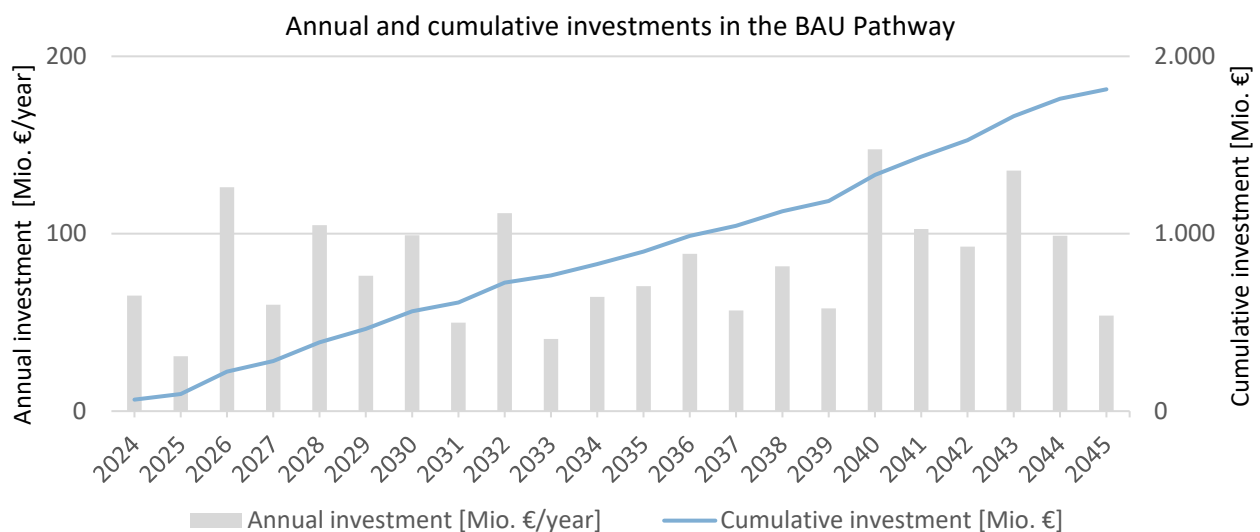


Figure 7 Annual and cumulative investment in the BAU Pathway

4.2 Electrification Pathway

The Electrification Pathway outlines the transformation of the German glass industry, assuming that direct electricity use in glass melting is maximised wherever technically feasible during the modelling period. The pathway therefore does not assume that all glass production can be converted to all-electric melting. Where full electrification remains technically constrained, particularly for large-scale flat glass production, the pathway retains highly electrified hybrid furnace concepts. The pathway starts from the 2024 furnace stock and applies site-specific assumptions about technological feasibility and furnace-rebuild cycles up to 2045.

Production capacities by technology

In the Electrification Pathway, conventional natural-gas-fired furnaces are replaced starting in 2024 by hybrid furnaces with increasing electricity shares and, where feasible, by all-electric melting furnaces, as shown in **Figure 8**. By 2030, the change is already substantial. Conventional regenerative furnaces then account for 51% of modelled production capacity, down from 95% in 2024. Together, natural-gas-based hybrid and super-hybrid furnaces account for 43.7% of capacity in 2030, while all-electric

tronic furnaces account for 5.3%. Expressing the development as shares of production capacity makes clear that the first phase of the pathway is characterised primarily by hybridisation rather than an immediate large-scale shift to all-electric furnaces.

From the early 2030s onwards, the share of all-electric furnaces increases substantially. Conventional regenerative furnace capacity declines from 5.60 Mt/a in 2024 to 2.56 Mt/a in 2030, 1.02 Mt/a in 2035 and only 22,500 t/a in 2040. Natural-gas-based hybrid capacities also decline thereafter, and the model phases out natural-gas-based furnace capacity by 2043. All-electric melting capacity, by contrast, increases from 45,600 t/a in 2024 to 0.26 Mt/a in 2030, 1.51 Mt/a in 2035 and 3.72 Mt/a in 2045.

In 2045, 71.7% of total modelled production capacity operates in all-electric furnaces. The remaining 28.3%, or 1.47 Mt/a, operates in hydrogen-based hybrid furnaces. In the model configuration, this remaining hybrid capacity corresponds to the flat glass production for which complete electrification is not assumed to become technically feasible within the modelling horizon. The Electrification

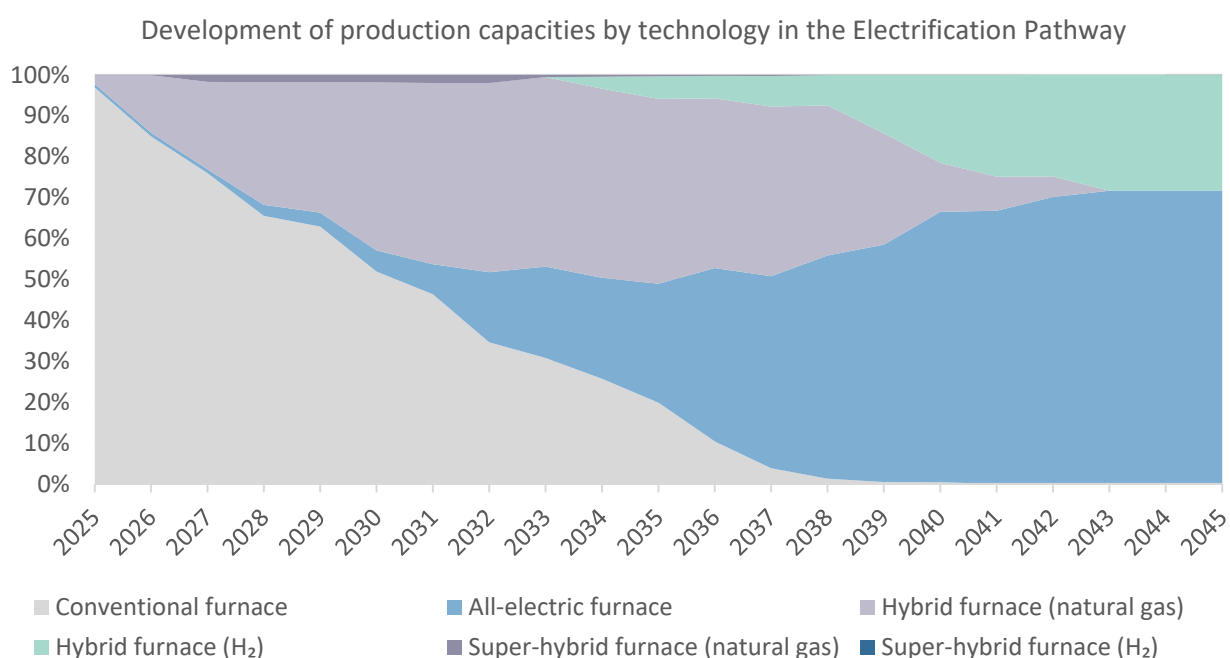


Figure 8 Development of production capacities by technology in the Electricity Pathway

Pathway should therefore be understood as a maximum-electrification pathway rather than as a scenario in which 100% of the furnace stock becomes fully electric.

This distinction is consistent with the technological assessment presented earlier in the roadmap. Current all-electric furnace concepts remain more readily applicable to smaller and medium-sized furnaces, whereas large-scale flat glass production continues to face greater technical constraints. The persistence of a hydrogen-based hybrid share in 2045 therefore reflects the technology assumptions rather than a deviation from the Electrification Pathway logic.

Energy consumption

The transformation of the furnace stock fundamentally changes the sector's energy-carrier structure, as shown in **Figure 9**. Natural-gas demand decreases from 41.1 PJ in 2024 to zero by 2045. At the same time, electricity demand increases from 8.1 PJ to 26.0 PJ in 2045. This is a 220% increase, with electricity demand reaching 7.21 TWh/a in the target year. Hydrogen is introduced for the remaining highly electrified hybrid furnace configurations and reaches 7.3 PJ/a, equivalent to 2.03 TWh/a, in 2045. For comparability, we report energy quantities primarily in PJ throughout the pathway analysis; TWh values are provided only as supplementary conversions. Using a higher heating value (Ho) of 39.4 kWh/kg H₂ for the energy-to-mass conversion, the

modelled hydrogen demand of 7.3 PJ/a corresponds to 51,500 t H₂/a in 2045.

Total final energy demand declines from 49.2 PJ in 2024 to 33.3 PJ in 2045, a reduction of 32.4%. This decline is substantially greater than the reduction in modelled production capacity. Consequently, specific final energy demand falls from 8.35 GJ/t in 2024 to 6.41 GJ/t in 2045, a 23% reduction. This indicates that the overall decline in energy demand in the Electrification Pathway reflects not only lower production capacity but also the higher energy efficiency of increasingly electrified melting technologies. The main reason is reduced thermal losses associated with combustion-based melting. As the electrical share increases, less energy leaves the furnace through hot combustion gases.

Pathway modelling focuses primarily on melting furnace transformations. However, the modelled final energy demand also includes energy consumption for feeders, forming processes, and annealing lehrs, as these are included in the site-level energy balances. In contrast, we do not explicitly model other auxiliary processes, particularly compressed-air generation and drives.

Many downstream and auxiliary processes are already predominantly electricity-based. Nevertheless, site-level decarbonisation planning must account for remaining fossil-fuel applications and additional electricity requirements, particularly for processes outside the explicit model scope. This is

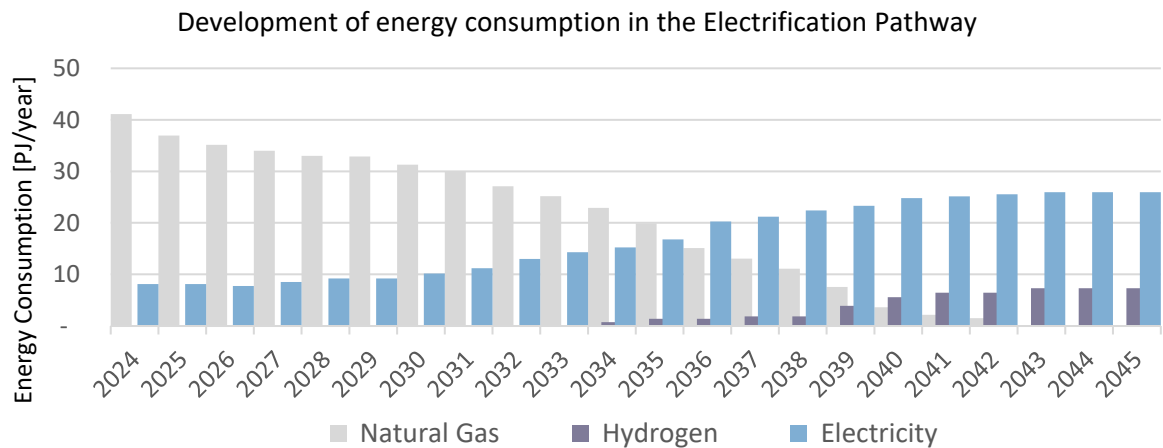


Figure 9 Development of energy consumption in the Electrification Pathway

especially important when dimensioning grid connections and internal electrical infrastructure alongside the increasing electricity demand associated with melting technologies. The energy values shown in **Figure 9** therefore reflect the defined modelling boundaries, while implementation planning requires an integrated assessment of the entire production line.

CO₂ emissions

The Electrification Pathway leads to a pronounced decline in both direct fuel-related and indirect electricity-related CO₂ emissions, as shown in **Figure 10**. Fuel-related emissions fall from 2.27 Mt CO₂/a in 2024 to zero in 2045 as natural gas is fully phased out, with the model assuming that hydrogen supplies the remaining gaseous energy demand. Indirect emissions from electricity consumption decline from 0.81 Mt CO₂/a in 2024 to zero in 2045, reflecting a progressive decarbonisation of the electricity supply and an electricity emission factor of 0 t CO₂/MWh in the target year. Process-related emissions decline only moderately, from 568,000 t CO₂/a in 2024 to 492,000 t CO₂/a in 2045. This reduction

mainly reflects lower modelled production capacity rather than electrification of the melting process, because electrification does not prevent CO₂ release from carbonate raw materials during glass melting. Consequently, total modelled CO₂ emissions decrease from about 3.64 Mt CO₂/a in 2024 to about 0.492 Mt CO₂/a in 2045, an 86.5% reduction. Unlike the previous model version, the 2045 scenario has no indirect electricity-related emissions. The remaining emissions in the target year are therefore entirely process-related within the model.

Consequently, electrification alone does not achieve full climate neutrality. The remaining process-related emissions must be further reduced or addressed through complementary measures, such as higher cullet shares, alternative or pre-decarbonated raw materials, CCS, or, where an appropriate and sufficiently permanent utilisation route exists, CCU. The separate CCS Pathway for flat glass examines one of these complementary options in greater detail.

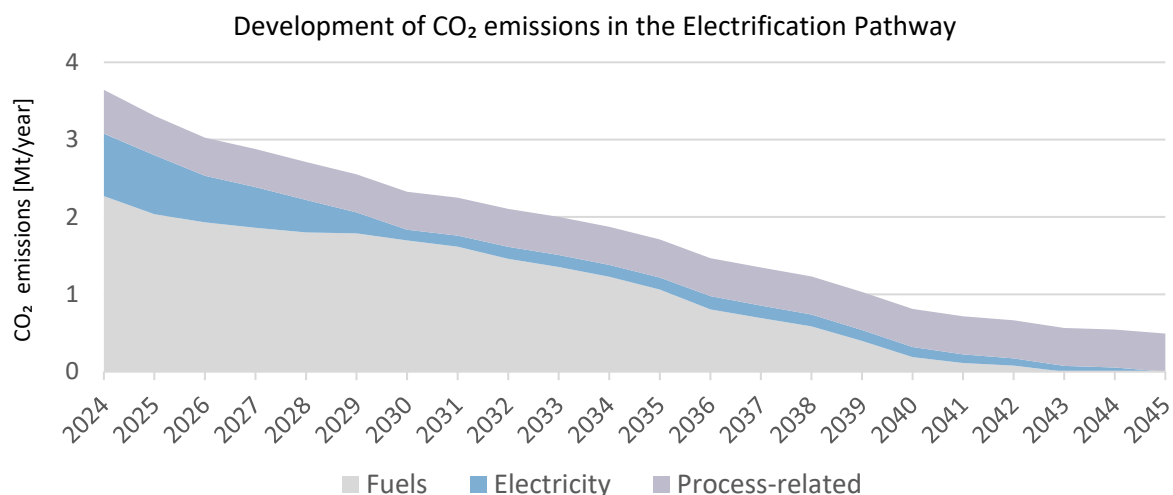


Figure 10 Development of CO₂ emissions in the Electrification Pathway

Investments

The transformation towards a predominantly electrically heated furnace stock requires substantially higher investment than the BAU Pathway. **Figure 11** shows the annual and cumulative investment requirements associated with the Electrification Path-

way. Annual modelled investment varies with furnace-rebuild cycles and the timing of technology replacement, ranging from €30.8 million to €574.6 million per year. Average annual investment over the period 2024–2045 amounts to €256 million. Cumulative investment reaches €5.64 billion by 2045. Compared with the cumulative investment of €1.84

billion in the BAU Pathway, the Electrification Pathway therefore requires €3.80 billion of additional modelled investment through 2045. This difference reflects both the transition to new furnace technologies and their respective replacement cycles.

The cumulative value should, however, be interpreted as the investment requirement within the model's boundaries and assumptions, rather than as a complete estimate of all expenditure needed to electrify individual production sites. Depending on the existing site infrastructure, implementation may require additional investments in transformers, substations, internal electricity distribution, higher-capacity grid connections and potentially upstream grid reinforcement. The actual investment requirement may therefore be higher at sites where substantial electrical infrastructure has to be newly constructed or expanded.

Other glass-sector assessments also support the importance of these additional infrastructure requirements. International analyses also identify electricity-grid capacity, connection upgrades, lead times, and electricity costs as key constraints on industrial-scale electrification. Therefore, assess the investment results alongside the site-specific electricity-infrastructure analysis presented later in the roadmap, rather than interpreting them as furnace costs alone.

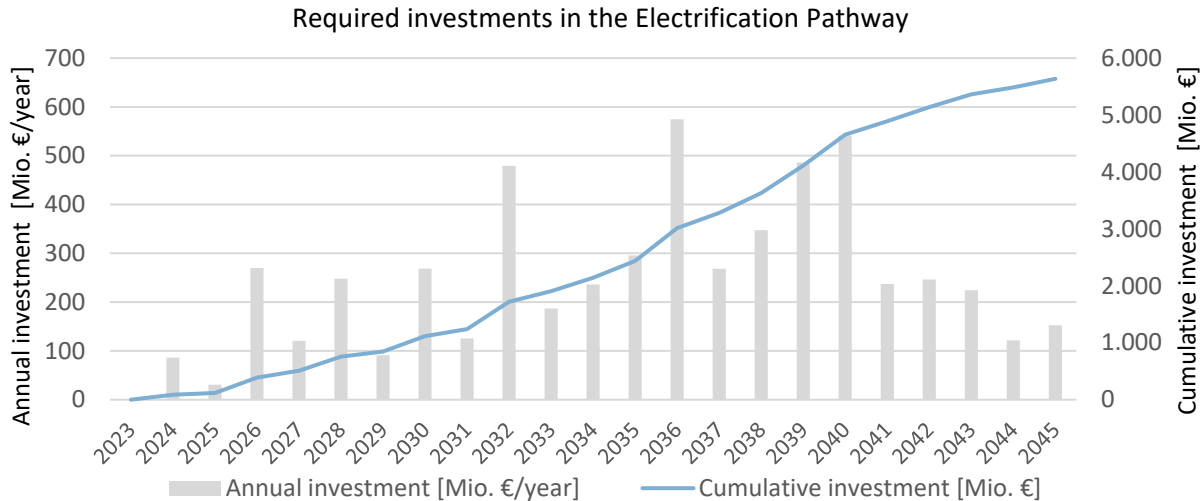


Figure 11 Required investments in the Electrification Pathway

4.3 Hydrogen Pathway

The Hydrogen Pathway describes the transformation of the German glass industry, assuming that decarbonisation is driven primarily by substituting natural gas with hydrogen in glass melting. It therefore represents an ambitious transformation case that maximises hydrogen-based furnace operation, assuming this is technically feasible within the pathway. The pathway does not imply that all furnaces operate exclusively on hydrogen: electricity remains an integral part of hybrid furnace concepts. In contrast, the pathway retains or introduces all-electric furnaces where they are assumed to be technically appropriate. The pathway starts with the 2024 furnace stock data and corresponding site-specific assumptions on technological feasibility, reinvestment cycles, and the expected development of hydrogen infrastructure in Germany. Hydrogen availability is therefore an important pathway assumption and should not be interpreted as a forecast of guaranteed site-level supply.

Production capacities by technology

In the Hydrogen Pathway, conventional natural-gas-fired furnaces are progressively replaced over their respective rebuild cycles as shown in **Figure 12**. During the transition, natural-gas-based hybrid furnaces initially serve as a bridging technology. As hydrogen availability expands, these furnace concepts progressively convert the gaseous component from natural gas to hydrogen. All-electric melting furnaces remain part of the technology portfolio where hydrogen-based operation is not the preferred technical option.

Conventional furnace capacity declines from 5.52 Mt/a in 2024 to 3.00 Mt/a in 2030 and 1.33 Mt/a in 2035. By 2040, the model run retains only 5,000 t/a of conventional capacity, and conventional furnace capacity is eliminated by 2045. At the same time, natural-gas-based hybrid furnaces expand during the intermediate transition period before hydrogen-based configurations progressively replace them.

Hydrogen-based furnace capacity begins to increase more substantially during the 2030s. For example, capacity in 80% H₂/20% electricity hybrid

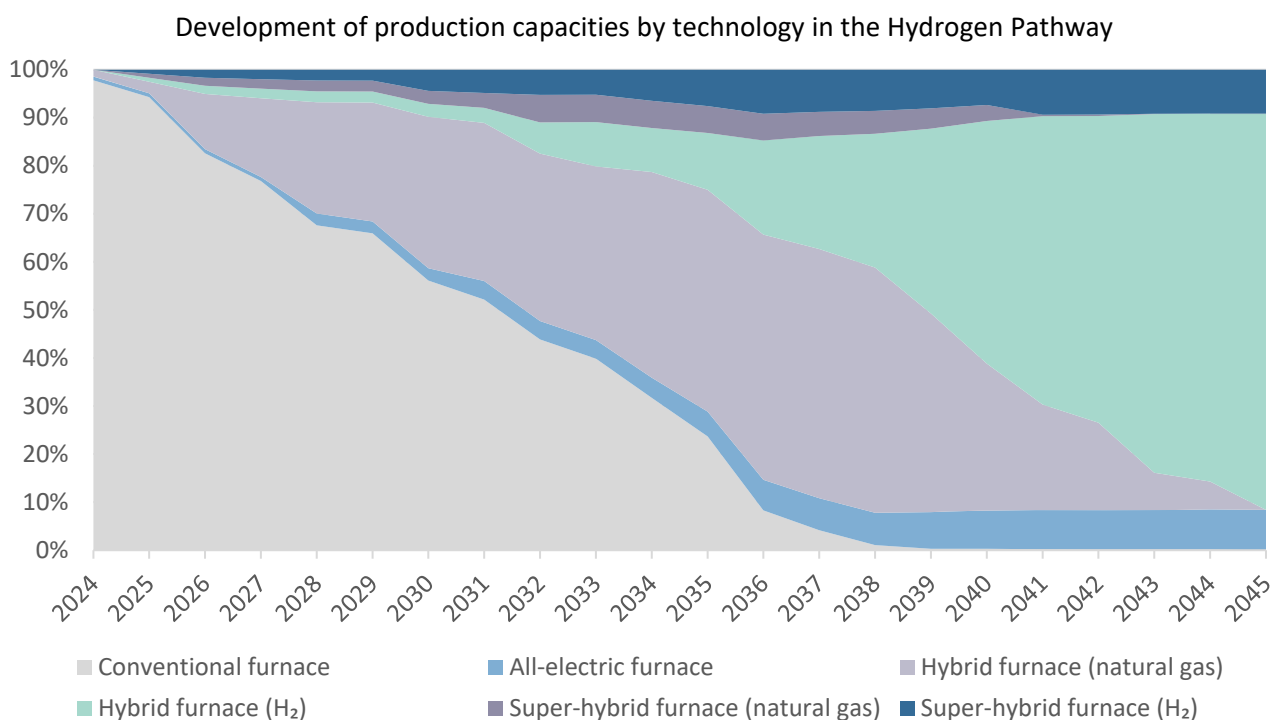


Figure 12 Development of production capacities by technology in the Hydrogen Pathway

furnaces rises to 1.93 Mt/a by 2045, while 60% H₂/40% electricity hybrid furnaces reach 2.39 Mt/a. More highly electrified hydrogen super-hybrid configurations provide additional production capacity. All-electric melting capacity increases from 45,600 t/a in 2024 to 414,000 t/a in 2045. Consequently, the 2045 furnace portfolio is dominated by hydrogen-based hybrid technologies, with only a small share of all-electric furnaces remaining.

The pathway should therefore be understood as hydrogen-dominant rather than exclusively hydrogen-based. Even in the Hydrogen Pathway, electricity demand remains substantial because hybrid furnaces combine hydrogen combustion with electric heating and because all-electric melting remains part of the furnace portfolio.

This result also reflects the technological assessment presented earlier in the roadmap. In principle, hydrogen can substitute for natural gas in glass melting. Still, its use requires adaptations to burners, combustion systems, control and safety equipment, and can affect furnace operation by changing flame and flue-gas characteristics. Underlying technical uncertainties include higher combustion temperatures, NO_x formation, changes in water-vapor

concentrations, and potential corrosion effects on furnace and regenerator materials. Comparable sector studies identify the same challenges.

Energy consumption

Figure 13 shows the resulting change in energy consumption. Natural-gas consumption declines from 41.1 PJ in 2024 to zero by 2045, while hydrogen demand increases from a negligible level to 24.2 PJ/a in the target year. This corresponds to 6.72 TWh/a, or 171,000 t H₂/a, based on a higher heating value (HHV) of 39.4 kWh/kg H₂.

At the same time, electricity demand increases from 8.1 PJ/a in 2024 to 14.5 PJ/a in 2045, corresponding to 4.02 TWh/a. Electricity therefore remains a substantial energy carrier even in the Hydrogen Pathway because hydrogen-based hybrid furnaces retain an electrical share and all-electric furnaces remain part of the technology portfolio. Overall final energy demand decreases from 49.2 PJ/a in 2024 to 38.7 PJ/a in 2045. This development reflects both reduced modelled production capacity and increased use of hybrid and electric furnace concepts, which have lower thermal losses than conventional regenerative furnaces.

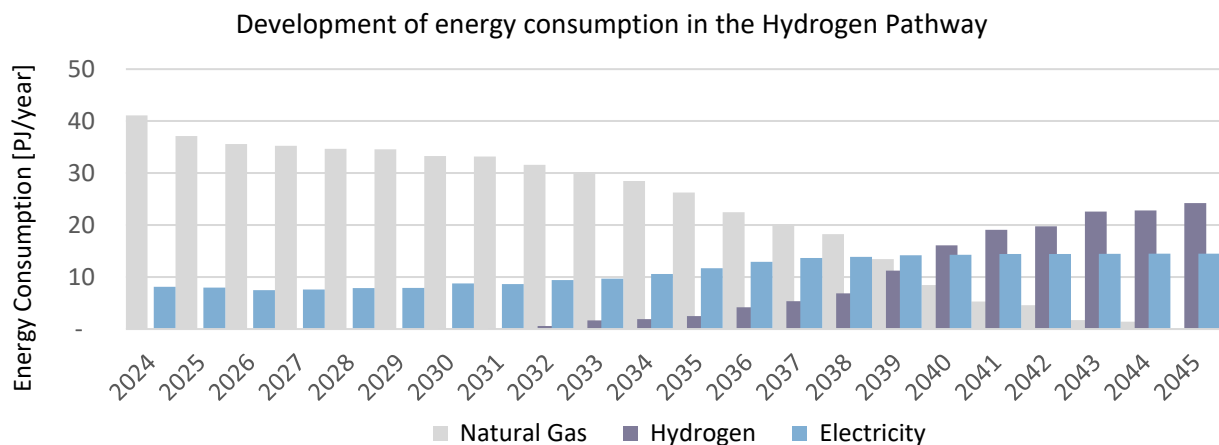


Figure 13 Development of energy consumption in the Hydrogen Pathway

CO₂ emissions

The Hydrogen Pathway significantly reduces total CO₂ emissions as shown in **Figure 14**. Fuel-related CO₂ emissions decline to zero by 2045 as natural gas is phased out and replaced by hydrogen and electricity. Indirect CO₂ emissions from electricity consumption also reach zero in 2045, reflecting the assumed complete decarbonisation of the electricity supply. Process-related CO₂ emissions remain the sole source of residual emissions in 2045, amounting to approximately 0.492 Mt CO₂/a.

Total annual emissions therefore decline from approximately 3.64 Mt CO₂/a in 2024 to 0.492 Mt CO₂/a in 2045, corresponding to a reduction of approximately 86.5%. As in the Electrification and Hybrid Pathways, the remaining emissions come from decomposing carbonate-based raw materials during glass melting.

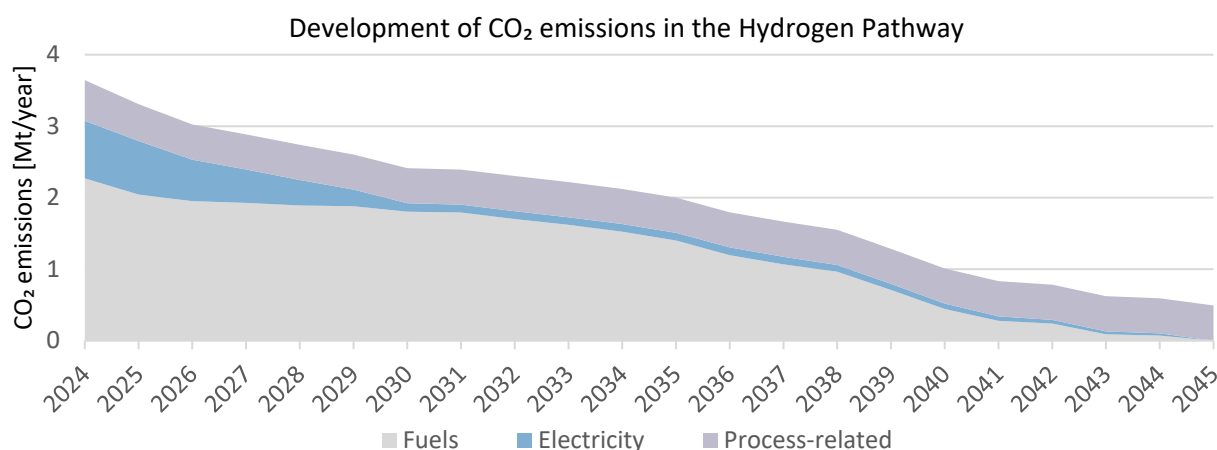


Figure 14 Development of CO₂ emissions in the Hydrogen Pathway

Investment

The Hydrogen Pathway requires substantial investment in both furnace conversion and site-level energy infrastructure. These investments include replacing or retrofitting melting furnaces, hydrogen-compatible burner systems, plant-side supply infrastructure, and the necessary technical adaptations

at production sites. Annual investment requirements range from €52 million to €349 million, depending on the timing of furnace rebuild cycles and the required conversion steps **Figure 15**.

Average annual investment amounts to approximately €171 million over the period from 2024 to

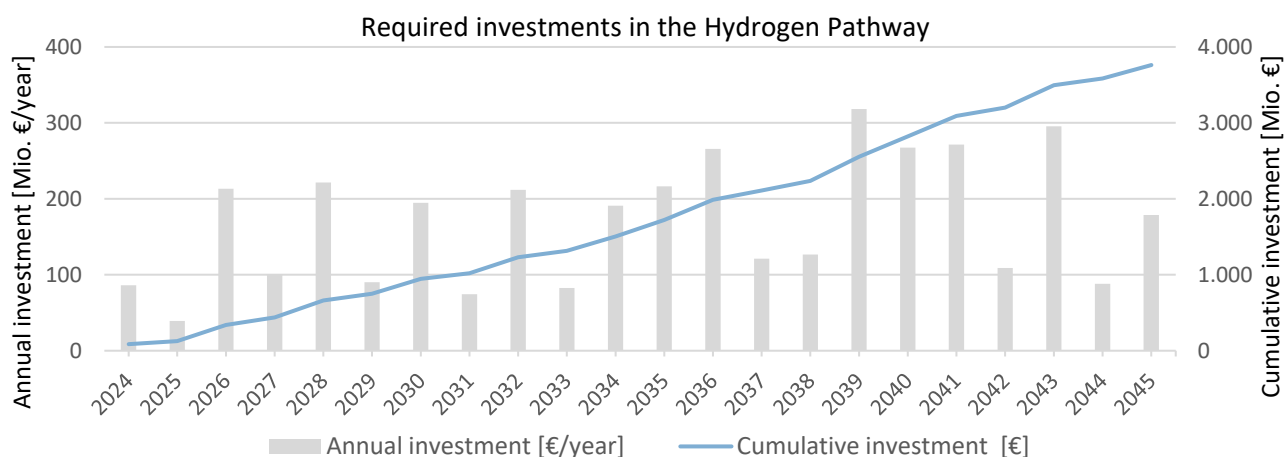


Figure 15 Required investments in the Hydrogen Pathway

2045. Cumulative investment requirements reach €3.76 billion by 2045, corresponding to €1.92 billion above the BAU Pathway. The Hydrogen Pathway therefore requires lower modelled plant-level investment than the Electrification and Hybrid Pathways. However, this does not necessarily make it economically more favourable overall, as the comparison excludes external hydrogen production and transport infrastructure and does not account for potentially higher hydrogen-related operating costs.

4.4 Hybrid Pathway

Unlike the Electrification and Hydrogen Pathways, the Hybrid Pathway does not maximise the deployment of a single energy carrier or furnace technology. Instead, it represents a differentiated transformation pathway in which the technological configuration is selected according to the specific requirements and boundary conditions of individual production sites and glass segments. The assessment considers product requirements, furnace size, rebuild cycles, technological feasibility, and the assumed availability of electricity and hydrogen infrastructure. The pathway was developed in close exchange with BV Glas and companies from the German glass industry and therefore reflects a sector-informed transformation strategy. It should nevertheless be understood as a scenario rather than as a forecast of the actual future furnace stock.

Hybridisation primarily serves as a bridging and risk-management strategy. In the first phase, electricity is increasingly combined with natural gas, as an immediate transition to all-electric melting is not assumed to be feasible. In later rebuild cycles, natural gas is progressively replaced by hydrogen, or the furnace is converted to an all-electric configuration where technically feasible. A hybrid furnace therefore is not a single fixed technology: the balance between electricity and the gaseous energy carrier varies by application and over time. This approach also allows the transformation to respond to different infrastructure developments and technological

constraints across hollow glass, flat glass and technical glass. Comparable sector assessments identify the same strategic advantage of hybrid concepts, particularly because furnace lifetimes extend over many years and the energy supply available at the next rebuild cannot be predicted with certainty.

At the same time, this strategic flexibility should not be confused with unrestricted short-term fuel switching during furnace operation. The technological assessment indicates that changes in the electricity-to-fuel ratio affect melt convection, temperature distribution, and product quality, and may require hours to days to stabilize. Higher electrical shares generally make short-term flexible operation more difficult, and repeated changes in the energy-carrier mix can negatively affect furnace lifetime.

The Hybrid Pathway is analysed both for the German glass industry as a whole and separately for hollow glass, flat glass, and technical glass to make these segment-specific transformation patterns visible.

4.4.1 Glass Industry as a whole

The following section summarizes the Hybrid Pathway results for the German glass industry.

Production capacities by technology

In the Hybrid Pathway, conventional natural-gas-fired furnaces are progressively replaced by all-electric and hybrid furnace concepts **Figure 16**. The model includes an initial adjustment of production capacity between 2024 and 2026: total modelled production capacity decreases from 5.89 Mt/a in 2024 to 5.19 Mt/a in 2026. After this initial adjustment, the model assumes no further market-driven plant closures, and total modelled production capacity remains constant until 2045. This represents an optimistic boundary condition of the pathway and should not be interpreted as a forecast that no further capacity losses will occur in the German glass industry.

During the first transformation phase, natural-gas-based hybrid furnaces serve as a bridge technology,

allowing the share of melting energy supplied by electricity to increase while conventional furnace capacity declines. In later rebuild cycles, these transitional configurations are progressively replaced by either hydrogen-based hybrid furnaces or all-electric furnaces. By 2045, the model phases out conventional natural-gas-based furnace capacity.

The resulting furnace portfolio in 2045 consists of 1.45 Mt/a of fully electric melting capacity and 3.74 Mt/a of hydrogen-based hybrid and super-hybrid capacity. This corresponds to 28% all-electric and 72% hydrogen-based hybrid production capacity. The high hybrid share should not be interpreted as low electrification: many of these furnaces are super-hybrid configurations in which electricity supplies most of the melting energy.

The development also demonstrates why the Hybrid Pathway differs from both the Electrification and Hydrogen Pathways. It retains more hydrogen-based furnace capacity than the Electrification Pathway, but combines this with substantially higher electrical shares than the Hydrogen Pathway. The final technology mix therefore reflects segment-specific technical assumptions rather than a predetermined sector-wide electricity-to-hydrogen ratio. CCS itself is assessed separately for flat glass and should not be presented as a component of the Hybrid Pathway.

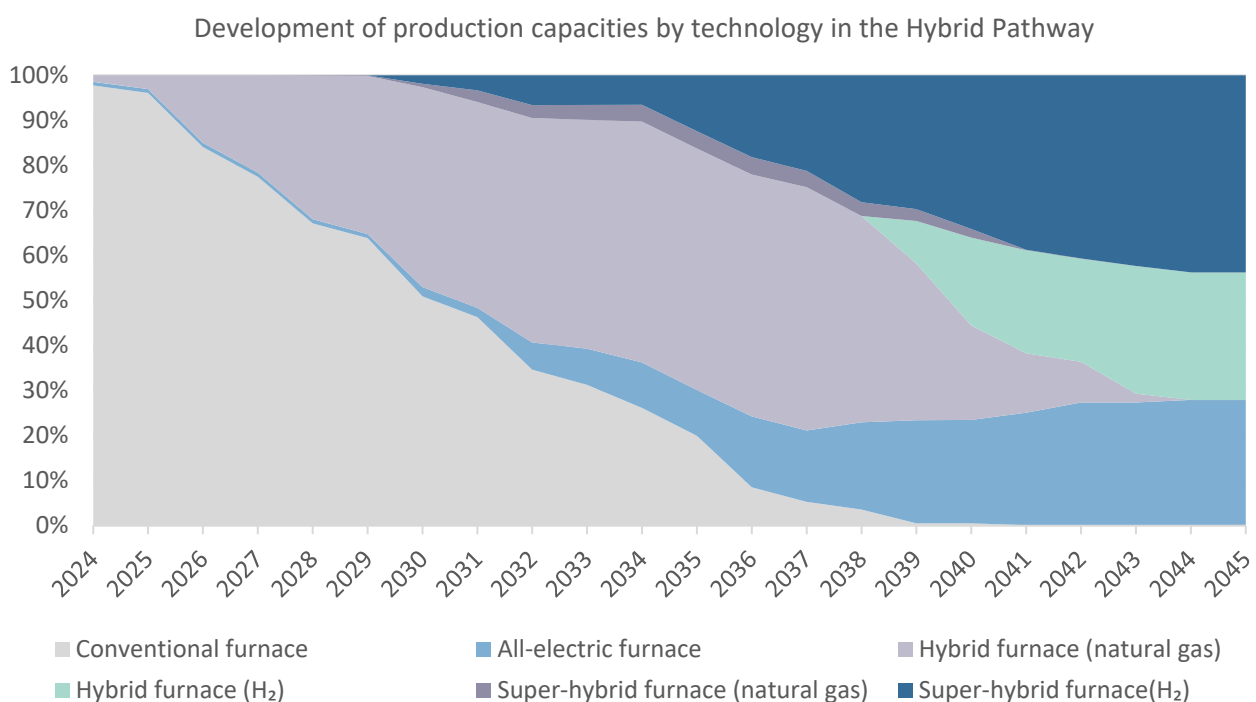


Figure 16 Development of production capacities by technology in the Hybrid Pathway

Energy consumption

Figure 17 shows the corresponding transformation of the energy-carrier mix. Natural-gas demand declines from 41.1 PJ/a in 2024 to zero by 2045. Electricity demand increases from 8.1 PJ/a to 24.8 PJ/a, while hydrogen demand rises from virtually zero to 12.0 PJ/a in the target year. Total final energy demand therefore amounts to 36.75 PJ/a in 2045.

Consequently, electricity is the dominant final energy carrier in 2045, accounting for 67% of total final energy demand, while hydrogen supplies 33%. This is an important correction compared with the previous model version: electricity demand in the Hybrid Pathway is slightly lower than in the Electrification Pathway (24.8 PJ compared with 26.0 PJ), whereas hydrogen demand is substantially higher

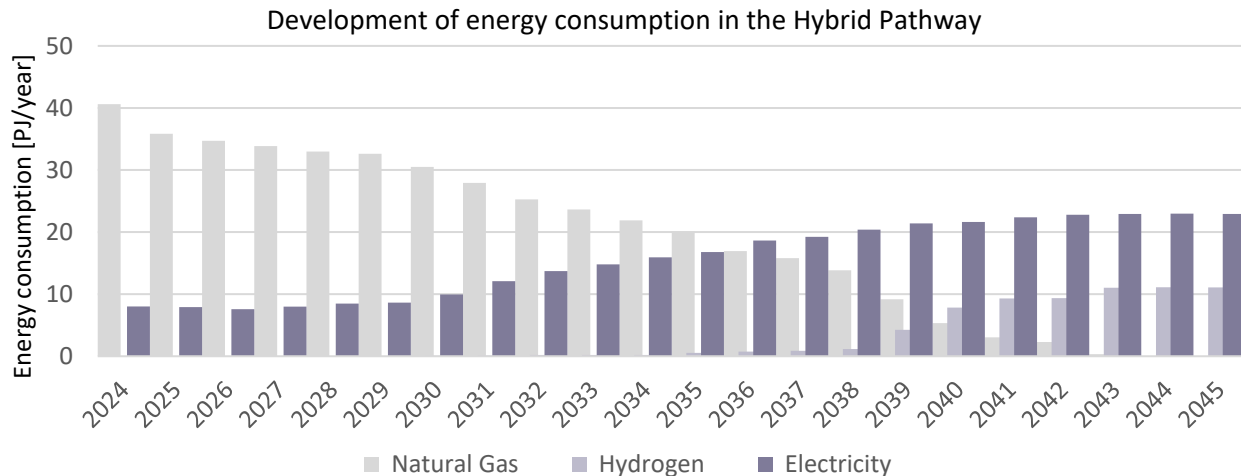


Figure 17 Development of energy consumption in the Hybrid Pathway

(12.0 PJ compared with 7.3 PJ). The Hybrid Pathway therefore falls between maximum electrification and maximum hydrogen use.

To align with the Hydrogen Pathway, hydrogen demand can also be expressed as a physical quantity. Based on the higher heating value (Ho) of 39.4 kWh/kg H₂ used throughout the roadmap, 12.0 PJ/a corresponds to 84,500 t H₂/a in 2045.

Despite rising electricity and hydrogen demand, total final energy consumption decreases from 49.2 PJ/a in 2024 to 36.75 PJ/a in 2045, a 25% reduction. Part of this decline results from the initial reduction in modelled production capacity. However, specific final energy demand also decreases from 8.35 GJ/t in 2024 to 7.08 GJ/t in 2045, a 15% improvement. The reduction in final energy demand therefore reflects both the initial capacity adjustment and the higher energy efficiency of the increasingly electrified furnace portfolio.

The pathway nevertheless creates substantial infrastructure requirements for both electricity and hydrogen. The assessment considers hydrogen supply risk higher than electricity supply risk. Electricity is already available at all production sites, although substantial increases in connection capacity and grid reinforcement may be required. Hydrogen, by contrast, requires developing a new supply system and may not become available at every site at the

required volume or by the required date. The Hybrid Pathway therefore reduces dependence on a single future energy carrier, but it does not remove infrastructure risk; instead, it requires the coordinated development of both electricity and hydrogen supply.

CO₂ emissions

Figure 18 shows, that the Hybrid Pathway substantially reduces total CO₂ emissions. Total modelled emissions decline from 3.64 Mt CO₂/a in 2024 to 0.492 Mt CO₂/a in 2045, an 86.5% reduction.

Fuel-related emissions decline progressively as natural gas is replaced and reach zero in 2045. Indirect emissions from electricity consumption likewise decline to zero under the model assumption that the electricity-grid emission factor reaches 0 t CO₂/MWh in the target year. The 0.492 Mt CO₂/a remaining in 2045 therefore consists entirely of process-related emissions from carbonate decomposition.

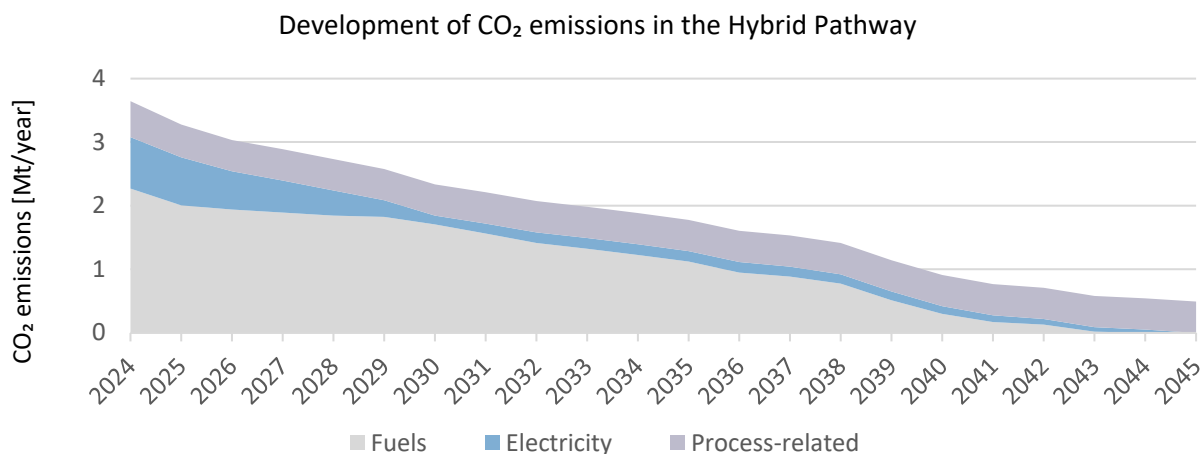


Figure 18 Development of CO₂ emissions in the Hybrid Pathway

The residual-emission level is essentially identical to that of the Electrification and Hydrogen Pathways in the current model run. The choice between the three transformation pathways therefore does not materially change the remaining process-emission burden in 2045; it mainly changes the required furnace technologies, electricity and hydrogen demand, infrastructure dependencies and investment profile. Additional measures are therefore needed to eliminate or offset these process-related emissions.

Investment

Figure 19 shows the Hybrid Pathway's annual and cumulative investment requirements. Annual investment is highly uneven because furnace replace-

ments follow individual rebuild cycles. In the current model run, annual investment ranges from €66 million to €568 million, with the highest annual investment requirement occurring in 2031. Average annual investment over 2024–2045 is €280 million. Cumulative investment reaches €6.15 billion by 2045. The Hybrid Pathway is therefore the most capital-intensive of the three transformation pathways in the current model run, exceeding both the Electrification Pathway (€5.64 billion) and the Hydrogen Pathway (€3.76 billion).

This result does not mean that hybrid furnaces are intrinsically more expensive than all alternative furnace concepts. Rather, cumulative investment reflects the specific sequence of furnace technologies, their assumed lifetimes and the number of rebuilds

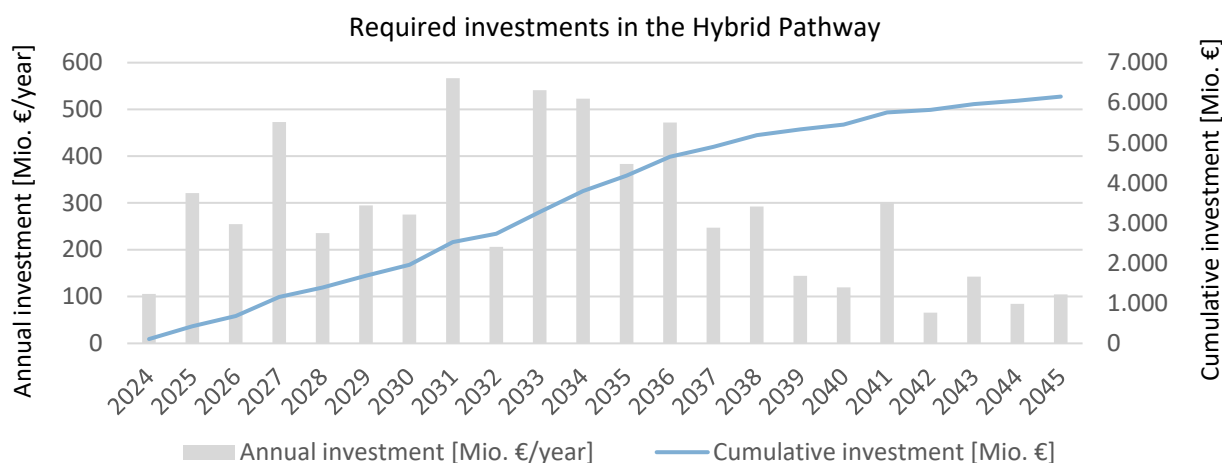


Figure 19 Annual and cumulative investments required for the implementation of the Hybrid Pathway in the German Glass Industry.

occurring over the modelling period. The Hybrid Pathway combines several successive technology stages and therefore involves substantial reinvestment over time. As in the other pathways, the modelled values should also be interpreted within the

defined system boundaries and may not capture all site-specific upstream grid or hydrogen-network investments.

4.4.2 Hollow Glass

Production capacities by technology

Figure 20 shows hollow glass development by segment. The model incorporates the initial capacity adjustment described above: hollow glass production capacity declines from about 3.81 Mt/a in 2024 to about 3.43 Mt/a by 2026 and then remains constant until 2045.

Within this remaining capacity, conventional furnaces are progressively replaced by increasingly electrified furnace concepts. Conventional capacity decreases from 3.66 Mt/a in 2024 to 1.89 Mt/a in 2030 and 0.58 Mt/a in 2035, then is completely phased out. In 2030, conventional furnaces still account for about 55% of hollow glass production capacity, while natural-gas-based hybrid configurations account for about 38%. All-electric furnaces

account for 2.5%, with the remaining capacity distributed across other transitional configurations. From the 2030s onward, the share of electric melting capacity increases considerably. By 2045, all-electric melting capacity reaches 1.34 Mt/a, corresponding to 39% of hollow glass capacity. The remaining 2.09 Mt/a, or 61%, is produced in hydrogen-based super-hybrid furnaces. Of this, 1.86 Mt/a is the highly electrified 20% H₂/80% electricity configuration, and 0.23 Mt/a is the 40% H₂/60% electricity configuration. Hollow glass production in 2045 is therefore predominantly electrified, even though most capacity is formally classified as hybrid rather than fully electric.

This distinction matters: interpreting technology shares based only on the labels “fully electric” and “hybrid” would underestimate the actual role of electricity, since super-hybrid technologies obtain 60% to 80% of their melting energy from electricity.

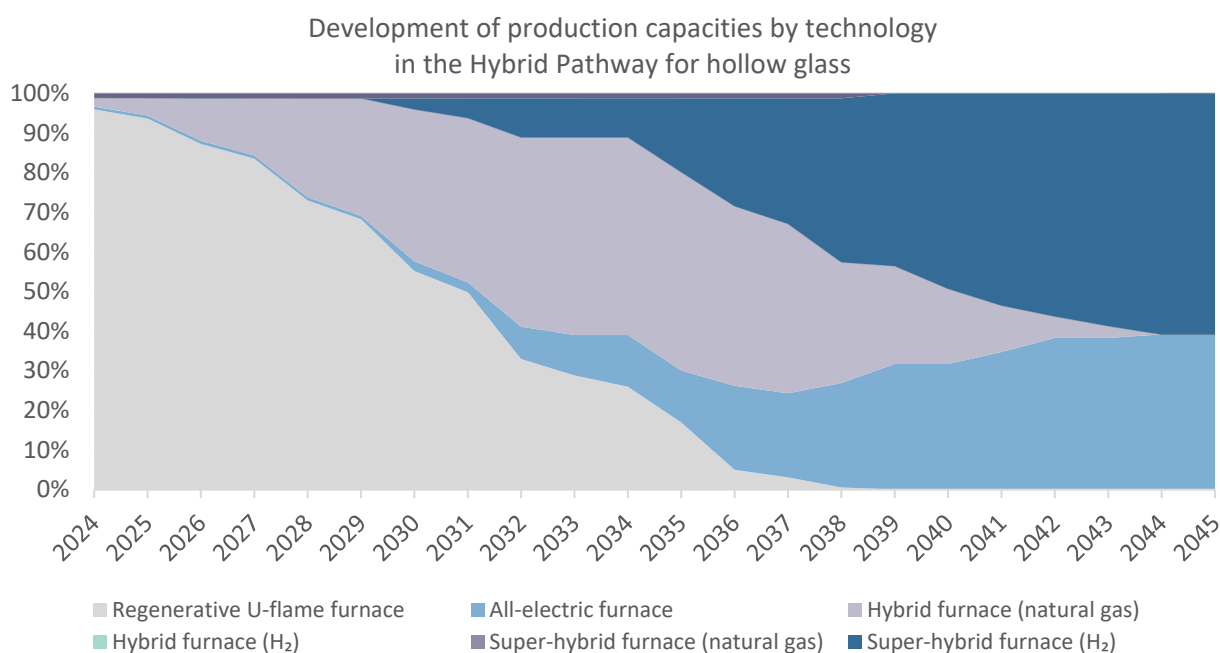


Figure 20 Distribution of production capacities by technology in the hollow glass sector in the Hybrid Pathway.

Energy consumption

Figure 21 shows the resulting change in energy demand. Natural-gas consumption declines from 18.74 PJ/a in 2024 to zero in 2045. Electricity demand rises from 4.08 PJ/a to 13.66 PJ/a, while hydrogen demand reaches 1.64 PJ/a. Total final energy demand therefore decreases from 22.81 PJ/a to 15.30 PJ/a.

The decline in absolute energy demand amounts to 33%. Because hollow glass production capacity also declines during the initial adjustment, specific energy demand provides a more meaningful indicator of efficiency. It falls from 5.99 GJ/t in 2024 to 4.46

GJ/t in 2045, a 26% improvement. The hollow glass segment therefore shows a substantial efficiency gain in addition to the capacity effect.

This result reflects the comparatively high degree of electrification assumed for hollow glass. All-electric and highly electrified super-hybrid furnaces reduce combustion-related flue-gas losses and therefore require less final energy per tonne of glass. This result is consistent with sector literature, which reports substantially higher efficiencies for highly electrified and all-electric melting than for conventional combustion-based furnaces.

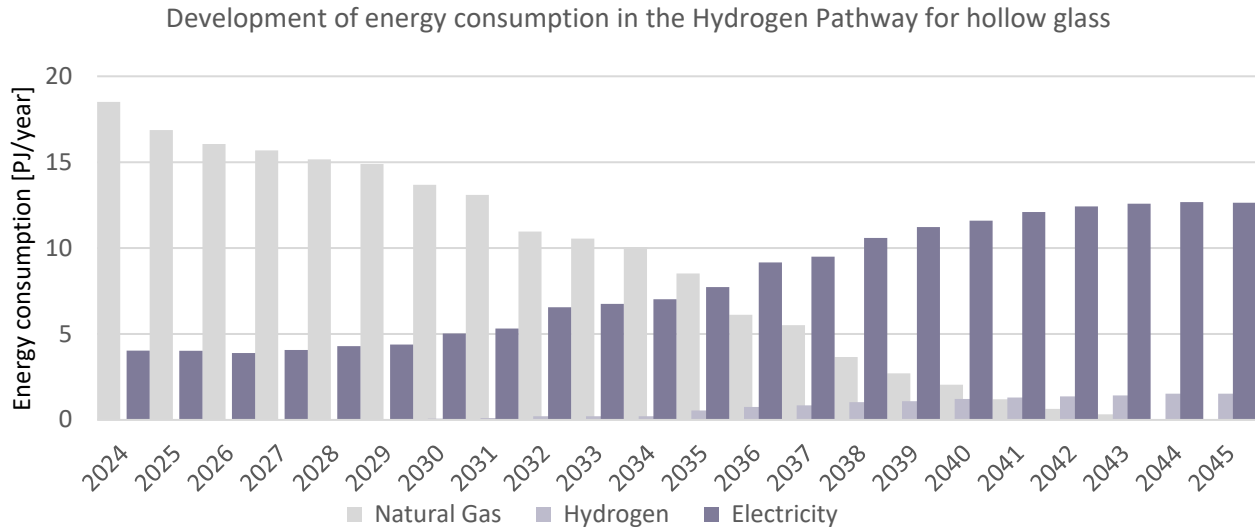


Figure 21 Development of energy consumption in the hollow glass sector in the Hybrid Pathway.

CO₂ emissions

Total annual CO₂ emissions in hollow glass decline from 1.69 Mt CO₂/a in 2024 to 0.227 Mt CO₂/a in 2045 as shown in **Figure 22**. Under the pathway assumptions, the target year eliminates fuel-related and electricity-related emissions. The remaining 227 kt CO₂/a consists entirely of process-related emissions from carbonate raw materials.

The reduction therefore amounts to 87%. As in the overall pathway, the final residual emissions cannot be eliminated by the assumed change in furnace energy supply alone.

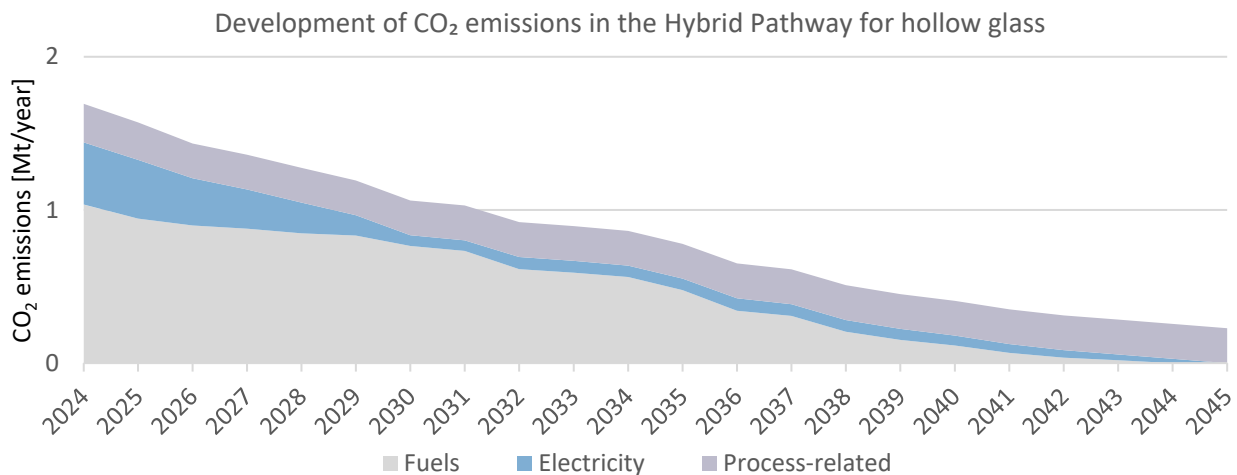


Figure 22 Development of CO₂ emissions in the hollow glass sector in the Hybrid Pathway.

Investment

The investment profile shown in **Figure 23** reflects the large number of furnace replacements and the transition through several increasingly electrified furnace configurations. Annual investment ranges

from €37 million to €474 million, depending on the rebuild schedule. Cumulative investment reaches €3.91 billion by 2045.

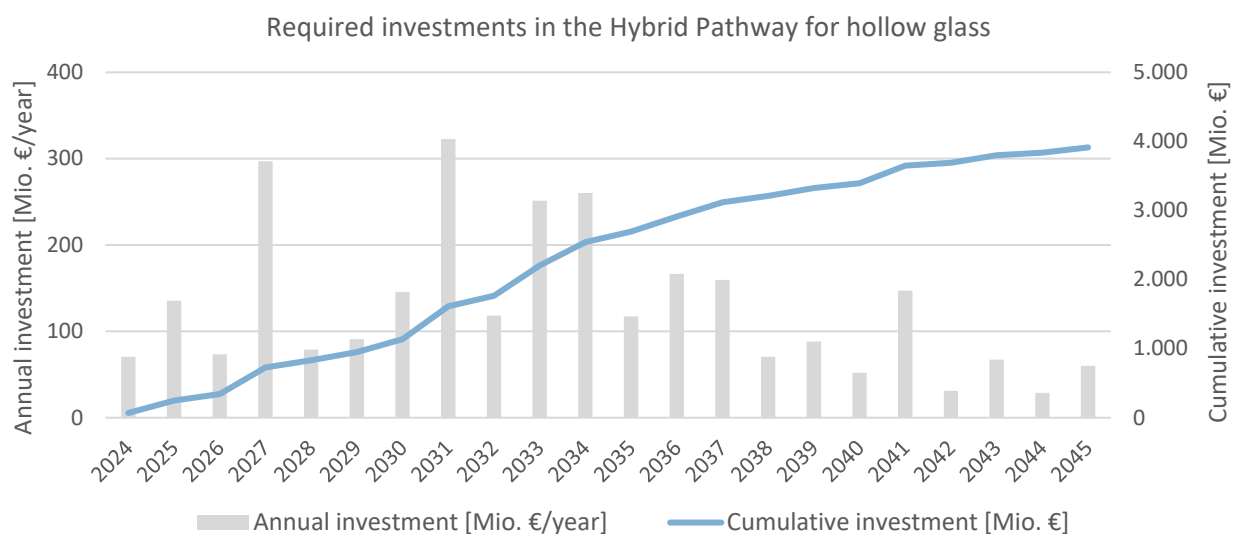


Figure 23 Required investments in the hollow glass sector in the Hybrid Pathway.

Hollow glass therefore represents the largest investment block within the Hybrid Pathway, accounting for 64% of total cumulative investment. This is partly due to the segment's size and the number of furnace units that must pass through their respective rebuild cycles.

Because furnace replacement timing is decisive for the transformation, a separate table showing the expected number of furnace rebuilds within the next ten years would provide useful additional information alongside **Figure 23**. However, this number should come directly from the furnace-level rebuild dataset rather than be inferred from changes in aggregate production capacity.

4.4.3 Flat Glass

Production capacities by technology

The flat glass pathway differs fundamentally from hollow glass because complete electrification of large float-glass furnaces is not assumed to become technically available within the modelling horizon.

As shown in **Figure 24**, the pathway therefore relies on a stepwise transition from conventional regener-

ative cross-fired furnaces towards hydrogen-capable hybrid furnaces rather than towards all-electric melting. Modelled flat glass capacity declines from about 1.79 Mt/a in 2024 to about 1.47 Mt/a by 2026, then remains constant. Conventional capacity decreases to 0.58 Mt/a by 2030 and is progressively replaced by natural-gas-based hybrid configurations during the transition. By 2045, conventional natural-gas-fired capacity has been completely phased out.

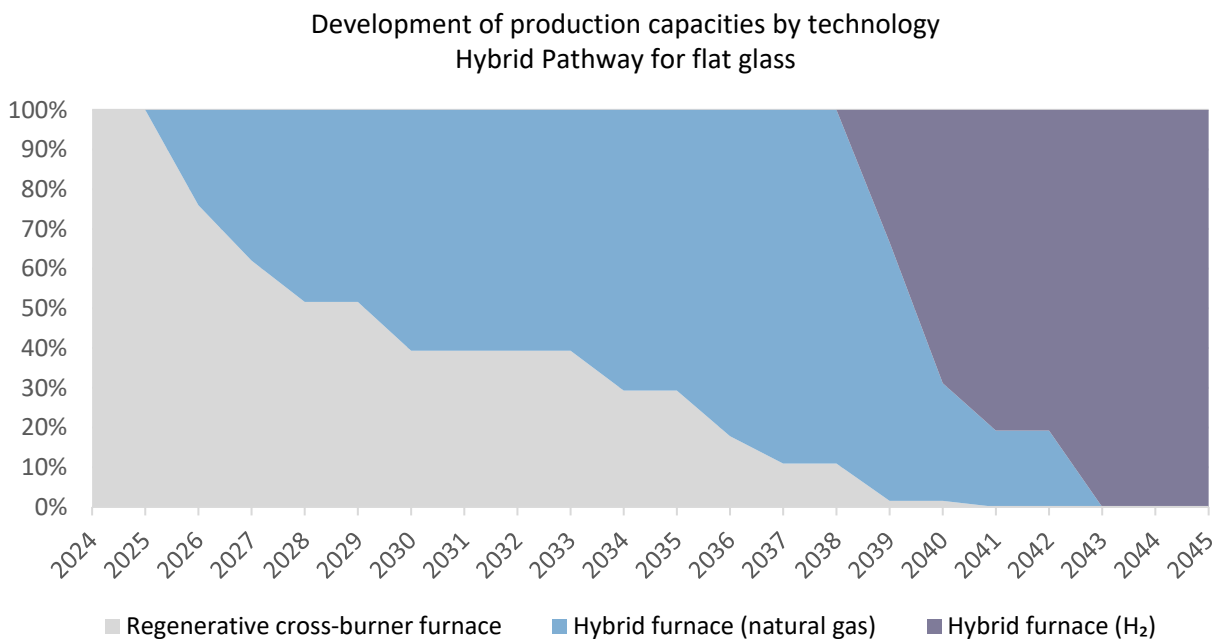


Figure 24 Distribution of production capacities by technology in the flat glass sector in the Hybrid Pathway.

Energy consumption

Figure 25 shows the strong dependence on gaseous energy carriers. Natural-gas demand declines from 16.87 PJ/a in 2024 to zero in 2045, while hydrogen demand rises to 9.77 PJ/a. Electricity demand increases from 0.44 PJ/a to 2.77 PJ/a. Consequently, total final energy demand decreases from 17.31 PJ/a to 12.54 PJ/a.

Hydrogen therefore supplies 78% of final energy demand in flat glass in 2045, compared with 22% from electricity. 9.77 PJ/a correspond to 68,900 t H₂/a on the H₀ basis used in this roadmap. Consequently, flat glass alone accounts for more than four-fifths of total hydrogen demand in the Hybrid Pathway.

Specific final energy demand decreases from about 9.65 GJ/t in 2024 to about 8.53 GJ/t in 2045, an improvement of about 12%. The efficiency improvement is therefore smaller than in hollow glass because the final furnace portfolio remains predominantly combustion-based, with hydrogen replacing natural gas and electricity taking a larger share.

This high hydrogen dependence makes flat glass particularly sensitive to the timing and location of future hydrogen infrastructure. The availability risk is therefore more pronounced in this segment than in hollow glass or technical glass, where the pathway relies more strongly on electricity.

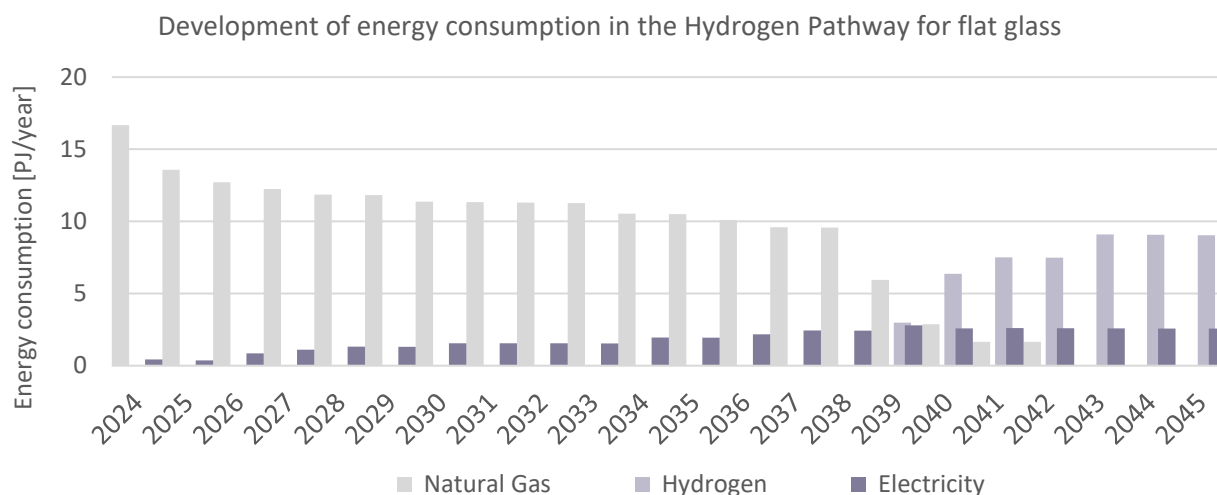


Figure 25 Development of energy consumption in the flat glass sector in the Hybrid Pathway.

CO₂ emissions

As shown in **Figure 26**, total annual CO₂ emissions decline from 1.26 Mt CO₂/a in 2024 to 0.231 Mt CO₂/a in 2045, an 82% reduction. Fuel-related emissions are eliminated as natural gas is phased out, while indirect electricity emissions reach zero under the assumed power-sector decarbonisation.

The remaining 231 kt CO₂/a in 2045 is entirely process-related. Flat glass therefore accounts for almost half of the remaining process emissions in the overall Hybrid Pathway, which is one reason the separate CCS Pathway is assessed specifically for this segment.

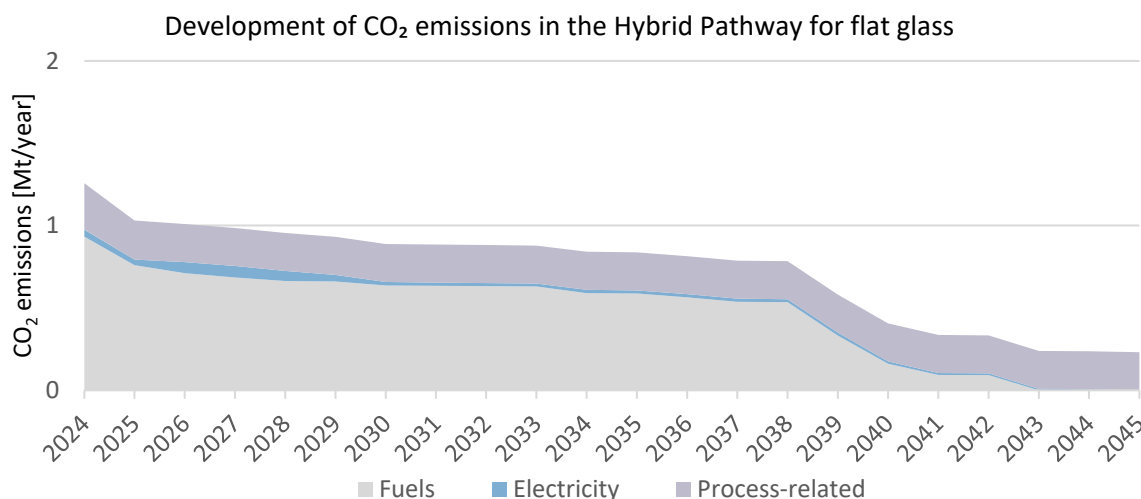


Figure 26 Development of CO₂ emissions in the flat glass sector in the Hybrid Pathway.

Investments

The annual and cumulative investment requirements are shown in **Figure 27**. In years with investment activity, annual expenditure reaches up to €164 million, while several years contain no modelled furnace investment because of the discrete rebuild schedule. Average annual investment over the full period amounts to €31 million. Cumulative investment reaches €0.69 billion by 2045.

Flat glass therefore represents the smallest investment block of the three segments in the current Hybrid Pathway, accounting for 11% of total cumulative investment. By comparison, hollow glass accounts for 64% and technical glass for 25%. The comparatively low cumulative flat-glass investment does not imply that individual float furnaces are inexpensive.

Rather, the segment includes far fewer large furnace units, and the modelled investment profile is driven by their specific rebuild cycles and the assumed costs of hydrogen-based hybrid technologies. The investment comparison must be interpreted together with infrastructure requirements. In particular, the 69,000 t H₂/a required by flat glass in 2045 creates an upstream supply requirement not fully captured by furnace CAPEX alone.

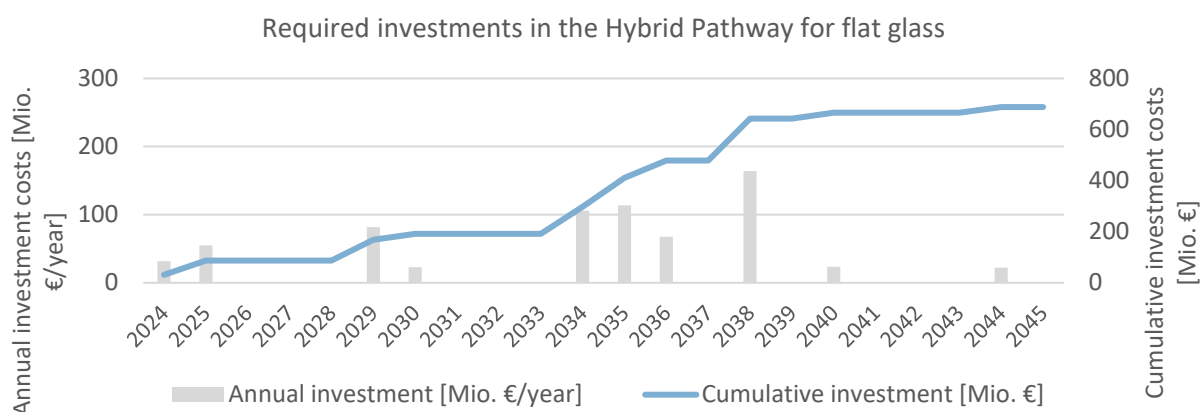


Figure 27 Required investments in the flat glass sector in the Hybrid Pathway

4.4.4 Technical & other Glass

Production capacities by technology

As shown in **Figure 28**, the technical glass segment follows a substantially more electricity-oriented transformation route. Total modelled production capacity remains constant at 0.286 Mt/a throughout the modelling period, while the furnace structure changes from conventional combustion towards all-electric and highly electrified super-hybrid concepts.

Conventional furnace capacity amounts to 0.268 Mt/a in 2024 and is progressively phased out during the 2030s. All-electric melting capacity increases from 18,400 t/a in 2024 to 104,000 t/a in 2045. In parallel, hydrogen-based 20% H₂/80% electricity super-hybrid furnaces reach 183,000 t/a in the target year. By 2045, 36% of technical glass capacity will be all-electric, and 64% will operate in highly electrified hydrogen super-hybrid furnaces.

The high share of electricity reflects two important characteristics of technical glass production. First, many technical glass products require comparatively high melting temperatures. In combustion-based furnaces, higher process temperatures increase the potential impact of thermal losses through the exhaust-gas stream, making it especially important to avoid combustion-related flue-gas losses with electric heating. Second, technical glass is frequently produced in smaller furnaces than hollow glass or flat glass. Smaller furnace capacities better match the current scale limitations of all-electric melting technologies and therefore enable greater electrification. These advantages nevertheless remain product-specific because glass composition, refining requirements and quality constraints differ substantially within the technical glass segment. This general direction aligns with sector literature showing that electric melting is currently most established at smaller furnace capacities and can achieve high energy efficiency.

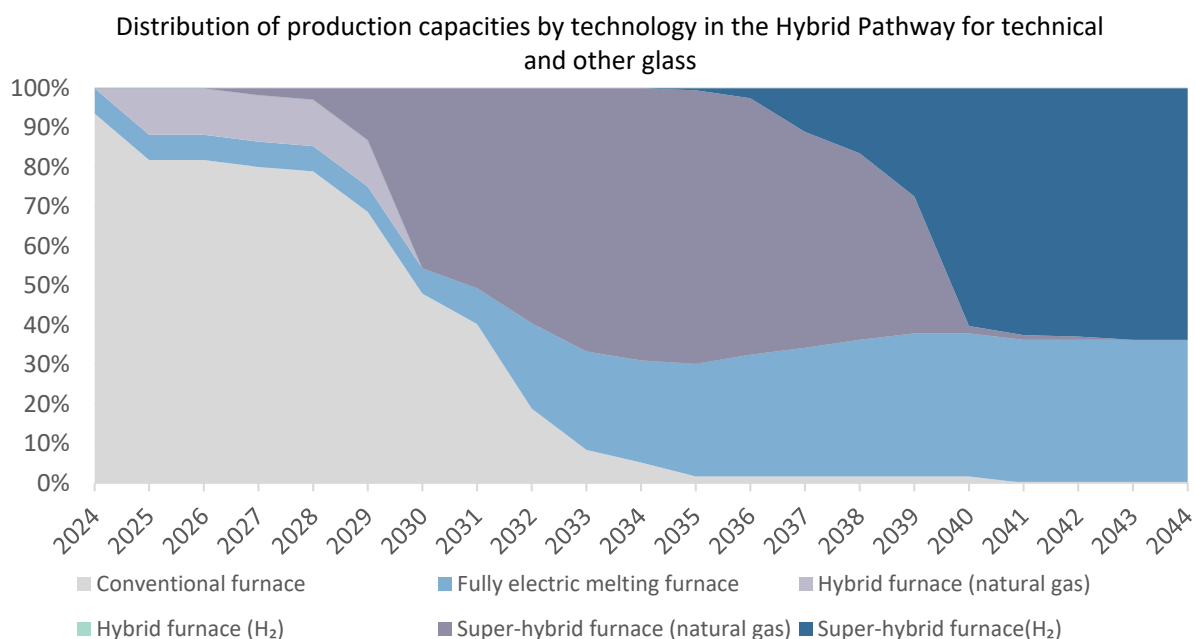


Figure 28 Distribution of production capacities by technology in the technical glass sector in the Hybrid Pathway.

Energy consumption

Figure 29 illustrates the resulting shift in energy carriers. Natural-gas demand decreases from 5.48 PJ/a in 2024 to zero by 2045. Electricity demand increases from 3.59 PJ/a to 8.33 PJ/a, while hydrogen

demand reaches 0.57 PJ/a. Total final energy demand therefore changes only moderately, from 9.08 PJ/a in 2024 to 8.90 PJ/a in 2045.

This development differs markedly from hollow glass. Specific final energy demand decreases only slightly, from 31.7 GJ/t to 31.1 GJ/t, a 2% improvement. The Hybrid Pathway's principal effect in technical glass is therefore to substitute the energy carrier rather than substantially reduce total final energy demand.

The comparatively high specific energy demand reflects the heterogeneous, energy-intensive production requirements of the technical glass segment. It should not be directly compared with hollow glass or flat glass as an indicator of furnace efficiency alone. Product-specific melting temperatures, smaller production scales and downstream processing requirements differ substantially between the segments.

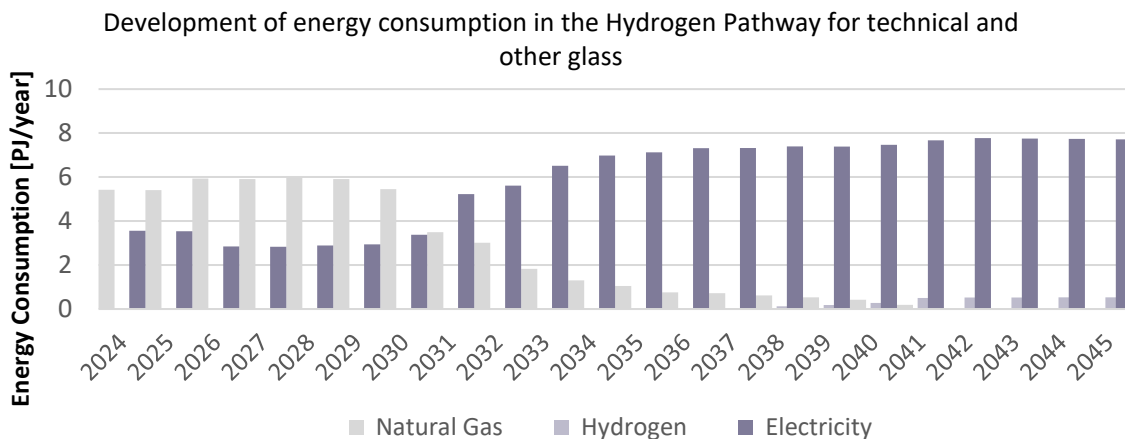


Figure 29 Development of energy consumption in the technical glass sector in the Hybrid Pathway.

CO₂ emissions

As **Figure 30** shows, total annual CO₂ emissions in technical glass decline from 0.694 Mt CO₂/a in 2024 to 33.5 kt CO₂/a in 2045, a 95% reduction. Fuel-related emissions are eliminated by phasing out natural gas, while indirect electricity-related emissions reach zero under the assumed grid decarbonisation. Unlike hollow glass and flat glass, process-related

emissions remain essentially constant at 33.5 kt CO₂/a throughout the modelling period because the model assumes no reduction in technical glass production capacity.

The decline in emissions therefore results almost entirely from changes in the energy supply rather than from changes in production volume.

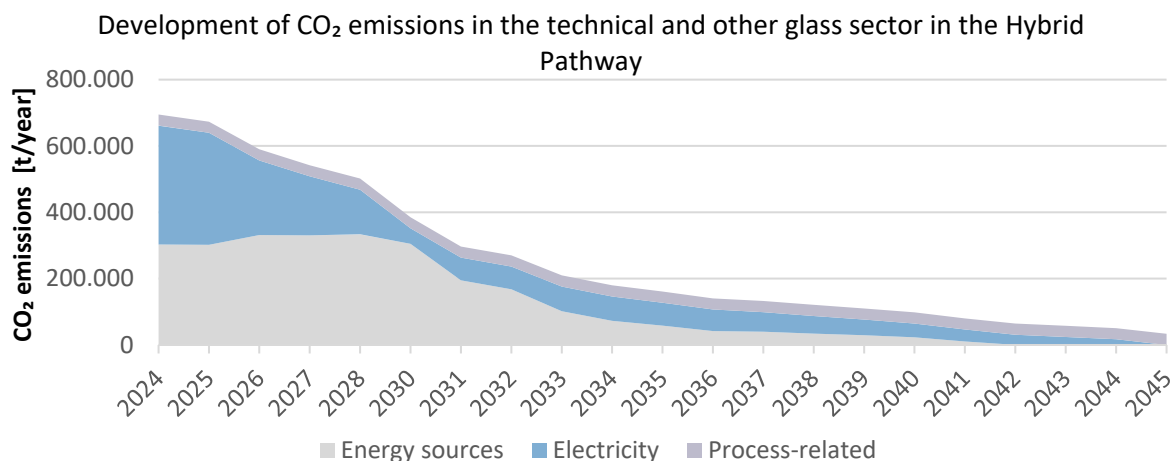


Figure 30 Development of CO₂ emissions in the technical and other glass sector in the Hybrid Pathway.

Investment

The annual investment requirements shown in **Figure 31** range from €3 million to €188 million, with a significant share occurring during the 2030s as all-electric and highly electrified hybrid concepts replace conventional furnaces. Cumulative investment reaches €1.55 billion by 2045.

Technical and other glass therefore account for 25% of cumulative Hybrid Pathway investment despite representing only 5.5% of modelled production capacity in 2045. This relatively high investment intensity reflects the segment's smaller furnace units and assumed replacement cycles.

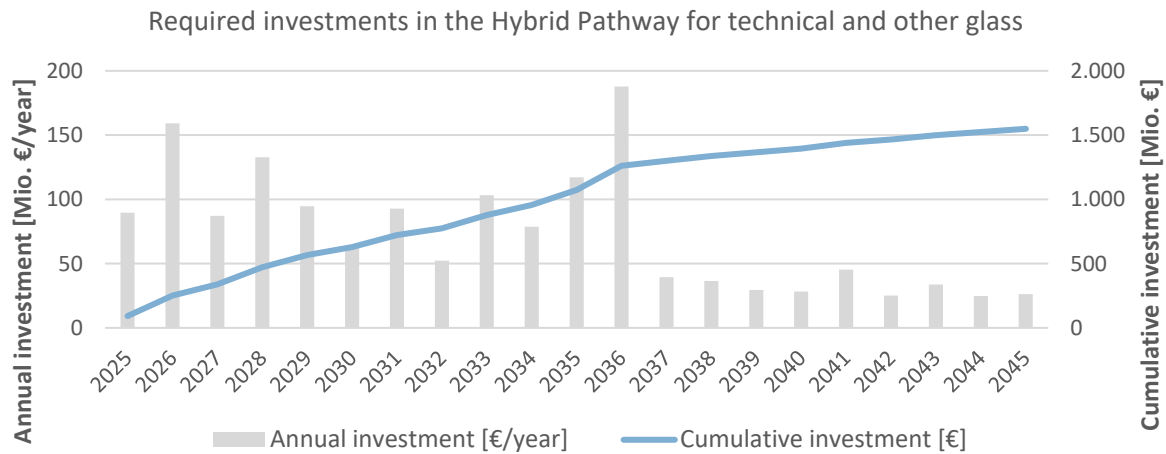


Figure 31 Required investments in the technical and other glass sector in the Hybrid Pathway.

4.4.5 Carbon Capture Storage and Utilization in the hybrid pathway

This roadmap considers CCS and CCU as a conditional transformation option for large flat glass production sites. It is not treated as a general decarbonisation pathway for the entire glass industry. It does not replace prior emission-reduction efforts through energy-efficiency measures, increased cullet use, electrification, hybrid furnace concepts or fuel switching. Instead, CCS provides an additional option for reducing residual emissions that remain difficult to avoid through these measures.

This is particularly relevant for process-related CO₂ emissions. During glass melting, CO₂ is released from the decomposition of carbonate raw materials such as limestone, dolomite and soda. These emissions remain even if the furnace energy supply is fully decarbonised. The other transformation pathways can therefore largely eliminate energy-related emissions. Still, they cannot achieve emission-free glass production as long as carbonate-based raw materials continue to be used.

The CCS pathway is considered exclusively for flat glass production. Float-glass furnaces represent the largest individual melting units in the German glass industry and combine high production capacities with particularly demanding requirements regarding process stability and product quality. At the same time, full electric melting is not assumed to become available for furnace sizes typical of float-glass production within the modelling period. The Hybrid Pathway therefore relies on hydrogen-based hybrid and super-hybrid furnace concepts for flat glass. CCS offers an alternative configuration in which large combustion-based furnaces can continue operating while capturing a major share of both energy- and process-related CO₂.

Within the roadmap, CCS becomes available from 2040 onwards. This does not imply that all flat glass furnaces will adopt carbon capture from that date. Instead, 2040 represents the earliest assumed de-

ployment under favourable technological, regulatory and infrastructural conditions. Hollow glass and technical glass follow the same development as in the Hybrid Pathway. The differences between the Hybrid and CCS Pathways therefore result exclusively from the alternative technological configuration of flat glass production from 2040 onwards.

Possible CO₂ capture configurations

Different technological configurations can, in principle, capture CO₂ from glass furnaces. Post-combustion capture separates CO₂ from the flue gas after combustion, for example through amine-based absorption. One potential advantage is that the capture unit can in principle be installed downstream of an existing combustion-based furnace. However, conventional air-fired furnace exhaust contains a comparatively low CO₂ concentration because a large amount of nitrogen enters the process with the combustion air. This increases the energy and equipment requirements for CO₂ separation.

Oxy-fuel combustion follows a different approach. Oxy-fuel combustion largely replaces combustion air with oxygen, substantially reducing the exhaust gas nitrogen content and increasing its CO₂ concentration. This provides more favourable conditions for subsequent carbon capture. However, oxy-fuel operation requires an adapted furnace and burner configuration, oxygen supply, appropriate furnace sealing and corresponding flue-gas treatment.

For consistency with the quantitative modelling, this roadmap assesses the CCS pathway based exclusively on natural-gas-fired oxy-fuel furnaces combined with carbon capture. Post-combustion amine capture and other possible capture configurations are considered technological alternatives but are not included in the quantitative energy, emissions and investment results presented below. Further developments, including electrically heated combustion-air systems and other innovative burner concepts, could change the relative attractiveness of the individual capture configurations and should therefore continue to be monitored.

CO₂ transport, storage and utilization

Carbon capture at the production site represents only the first part of the CCS chain. The captured CO₂ must subsequently be conditioned and transported to a suitable permanent storage site or, where applicable, to a utilization route.

The quantitative CCS pathway assumes pipeline transport for the eligible flat glass production sites. Access to CO₂ pipeline infrastructure therefore represents an important condition for implementing the pathway. Alternative transport options may nevertheless become relevant as future CO₂ infrastructure develops. Rail, ship, and inland-waterway transport could complement pipeline infrastructure or provide transitional solutions for sites that cannot initially connect directly to a pipeline network. These alternatives are not separately represented in the quantitative pathway.

Interpret the assumed transport and storage infrastructure as a scenario assumption rather than a project-specific infrastructure design. Actual costs and technical requirements will depend strongly on on-site location, transport distance, the size and utilisation of the CO₂ stream, connection conditions, storage location and the future development of shared CO₂ infrastructure. The roadmap therefore does not attempt to forecast the exact infrastructure configuration or cost for individual production sites.

CCU could provide an alternative destination for captured CO₂ in selected applications, for example as a feedstock for chemical products or in food and beverage applications. However, its potential contribution depends on future demand for captured CO₂, the permanence of carbon storage in the respective products and its regulatory treatment under the EU ETS. For these reasons, CCU's role in long-term industrial decarbonisation remains uncertain.⁴¹

Permanent geological storage therefore represents the primary destination assumed in the quantitative CCS pathway.

Production capacities by technology

The CCS Pathway assumes the same development of total flat glass production capacity as the other pathways (see **Figure 32**). In the CCS Pathway, no intermediate transition to hybrid furnaces is assumed. Until 2039, the entire flat glass production capacity remains assigned to conventional regenerative cross-fired furnaces. The transition to CCS begins in 2040, when 0.874 Mt/a of production capacity is transferred to natural-gas-fired oxy-fuel furnaces equipped with carbon capture, while 0.596 Mt/a remains in conventional regenerative furnaces. In 2041 and 2042, CCS capacity increases to 1.188 Mt/a, while conventional capacity declines to 0.282 Mt/a. From 2043 onwards, natural-gas-fired oxy-fuel furnaces equipped with CCS account for the full 1.470 Mt/a of flat glass production capacity (**Figure 32**).

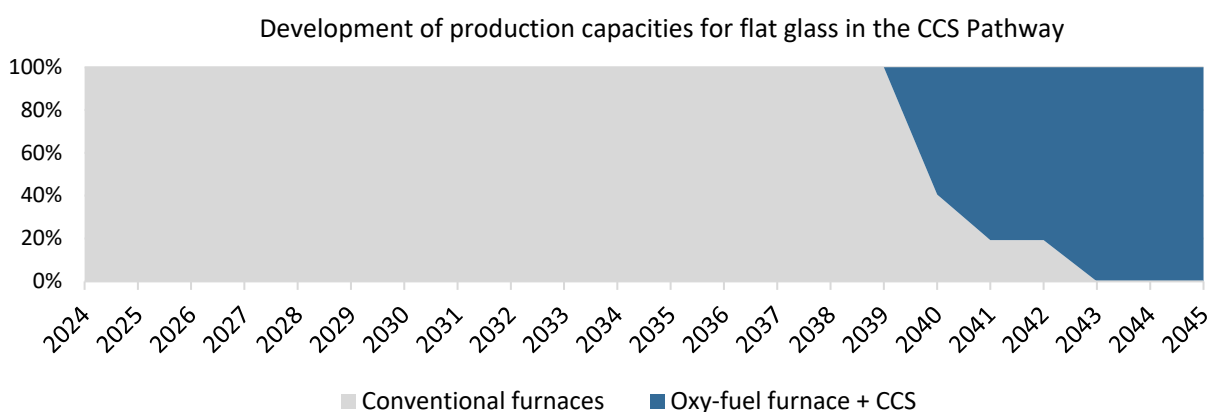


Figure 32 Development of production capacities for flat glass in the CCS Pathway

The pathway therefore avoids an intermediate investment in hybrid flat glass furnaces shortly before CCS becomes available. Instead, conventional furnaces remain in operation until the CCS transition begins, after which capacity shifts progressively to the oxy-fuel CCS configuration.

CCS abatement costs and economic conditions

The economic assessment of CCS is based on specific CO₂ abatement costs expressed in €/t CO₂ avoided. These costs represent the expenditure required to avoid one tonne of CO₂ through the CCS chain. Depending on the respective cost estimate, they include capture, CO₂ treatment and conditioning, compression or liquefaction, transport and geological storage.^{42,43}

For large-scale CCS applications, the roadmap applies cost assumptions associated with CO₂ point sources exceeding 100,000 t CO₂/a. This threshold refers to the annual amount of CO₂ available for capture, not the furnace's annual production capacity. This distinction is important. Flat glass furnaces can produce several hundred tonnes of glass per day and therefore considerably more than 100,000 tonnes of glass per year without necessarily emitting the same quantity of CO₂. Production capacity and capturable CO₂ flow must therefore be treated as separate parameters. Where several furnaces are

located at one production site, the relevant CO₂ stream may also need to be considered at the site level rather than the individual-furnace level.

As shown in **Figure 33**, the economic relevance of CCS depends strongly on the relationship between specific abatement costs and the cost of emitting CO₂ under the EU Emissions Trading System. As long as the cost of avoiding one tonne of CO₂ through CCS exceeds the effective cost of emitting the same tonne, the EU ETS alone does not provide a sufficient economic incentive for CCS investment. As CO₂ allowance prices rise and CCS costs potentially fall, this gap can narrow over time. The comparison therefore indicates when CCS becomes increasingly economically attractive relative to continued unabated emissions.

The intersection of the two cost developments should nevertheless not be interpreted as a strict investment threshold. Large upfront investments, infrastructure availability, long-term transport and storage contracts and technological risks remain relevant even if specific CCS abatement costs fall below the CO₂ allowance price. Additional public support and risk-sharing instruments may therefore remain necessary, particularly for first-of-a-kind installations and developing the required transport and storage infrastructure.^{42,43}

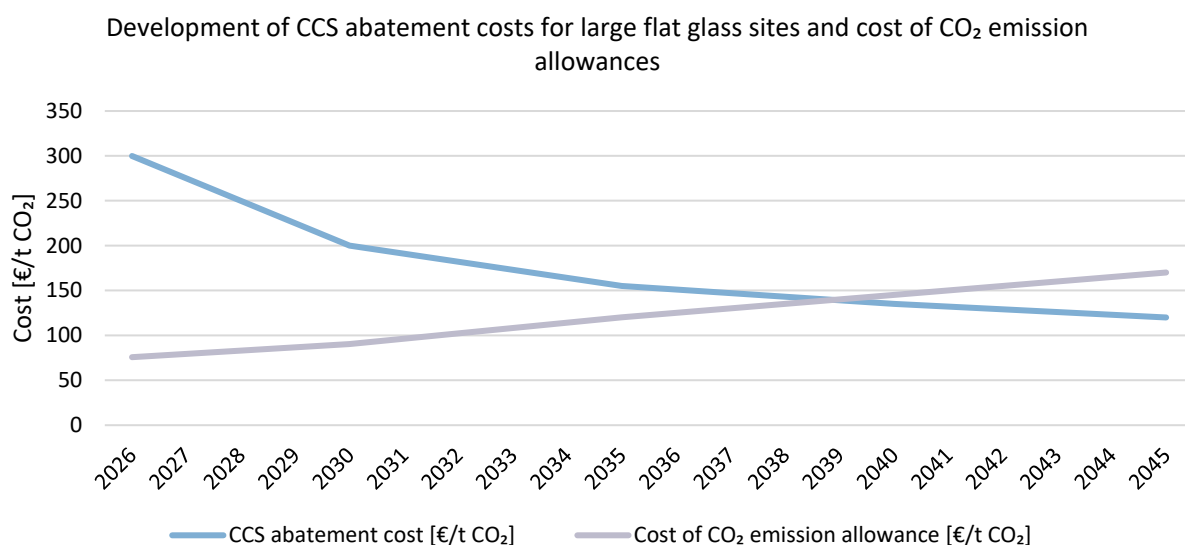


Figure 33 Assumed development of CCS abatement costs for large flat-glass sites, 2024–2045

The abatement-cost assumptions should likewise be interpreted as scenario-based estimates rather than as predictions of the actual costs at individual flat glass sites. Capture costs, transport tariffs, storage fees and infrastructure costs may differ substantially depending on plant configuration, scale, location and future market development.

Energy consumption

The development of the energy-carrier mix in the CCS configuration is illustrated in **Figure 34**. Until 2039, flat glass production remains based entirely on regenerative cross-fired furnaces. Natural gas therefore remains the principal energy carrier, while electricity demand is comparatively low.

The energy-carrier mix begins to change from 2040 onwards as conventional capacity is progressively replaced by natural-gas-fired oxy-fuel furnaces equipped with CCS. Natural-gas demand declines as oxy-fuel combustion reduces the amount of combustion gas that must be heated, lowering furnace fuel demand compared with conventional air-fired regenerative melting. At the same time, electricity demand increases because the CCS configuration requires additional electrical energy, particularly for oxygen supply and CO₂ capture, treatment and conditioning.

By 2045, natural-gas demand in the flat-glass CCS configuration is about 10.20 PJ/a, while electricity

demand reaches 1.13 PJ/a. Hydrogen is not used in this configuration. Total final energy demand therefore amounts to approximately 11.32 PJ/a.

Compared with the Hybrid Pathway, the CCS configuration requires less final energy in 2045. The Hybrid Pathway reaches approximately 12.54 PJ/a, consisting of 9.77 PJ/a of hydrogen and 2.77 PJ/a of electricity. The CCS configuration requires about 11.32 PJ/a, a reduction of 1.22 PJ/a (around 10 %). This difference reflects the technological assumptions of the modelled furnace configurations and should not be interpreted as a general energy-efficiency advantage of CCS.

The difference between the two pathways primarily reflects their fundamentally different furnace concepts. The Hybrid Pathway replaces natural gas through a combination of hydrogen and direct electrical energy input. In contrast, the CCS Pathway retains combustion-based melting but replaces conventional air firing with oxy-fuel combustion and adds the energy requirements associated with carbon capture.

The reduction in natural-gas demand in the CCS Pathway should therefore not be attributed to carbon capture itself. It results from the assumed higher efficiency of oxy-fuel combustion relative to conventional regenerative air-fired melting. Carbon capture, oxygen production, and CO₂ conditioning

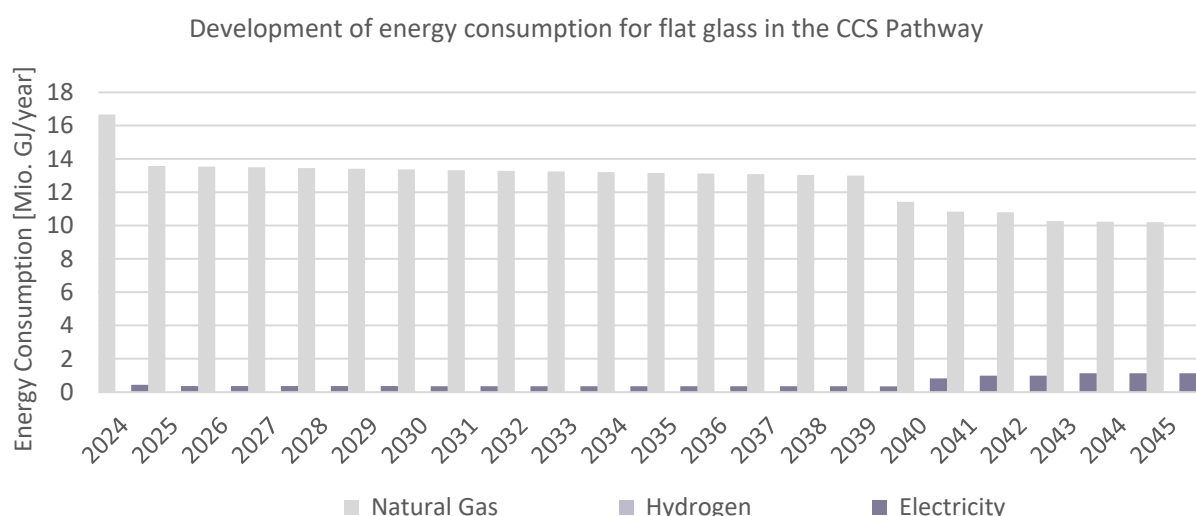


Figure 34 Development of energy consumption for flat glass in the CCS Pathway

add energy requirements that partly offset this efficiency advantage. CCS should consequently be interpreted primarily as an emission-reduction technology rather than as an energy-efficiency measure. Compared with the Hybrid Pathway, its main advantage is not lower energy demand but its ability to capture a substantial share of both fuel-related and process-related CO₂ emissions.

CO₂ emissions

Before introducing CCS, both natural-gas combustion and carbonate decomposition contribute to direct CO₂ emissions from flat glass production. As more production capacity shifts to oxy-fuel furnaces equipped with carbon capture, both emission sources can be substantially reduced, **Figure 35**. By 2045, residual emissions from flat glass production will amount to 83,663 t CO₂/a, or 0.084 Mt CO₂/a. These residual emissions consist of 60,574 t CO₂/a of energy-related emissions and 23,089 t CO₂/a of process-related emissions. The process-related component results directly from the assumed 90% capture rate. Without capture, process-related emissions at the 2045 production level amount to 230,885 t CO₂/a. Consequently, 10% remain after capture: $230,885 \text{ t CO}_2/\text{a} \times 10\% = 23,089 \text{ t CO}_2/\text{a}$.

$60,574 \text{ t CO}_2/\text{a} + 23,089 \text{ t CO}_2/\text{a} = 83,663 \text{ t CO}_2/\text{a}$, or 0.084 Mt CO₂/a.

In the Hybrid Pathway, fossil fuel-related emissions are largely eliminated by 2045, but process-related emissions from carbonate decomposition remain. Residual flat glass emissions therefore amount to 0.231 Mt CO₂/a. Compared with the Hybrid Pathway, CCS reduces residual flat glass emissions by about 0.147 Mt CO₂/a, or about 64%.

The principal advantage of the CCS configuration therefore lies in its ability to address both combustion-related and process-related CO₂ emissions. Fuel switching can largely eliminate fossil fuel-related emissions, whereas carbon capture can additionally reduce the process emissions that remain even when the energy supply is decarbonised. The remaining 0.084 Mt CO₂/a should not be interpreted as completely unavoidable emissions. They represent the residual emissions under the assumed 90% capture performance and the specific technological configuration represented in the roadmap.

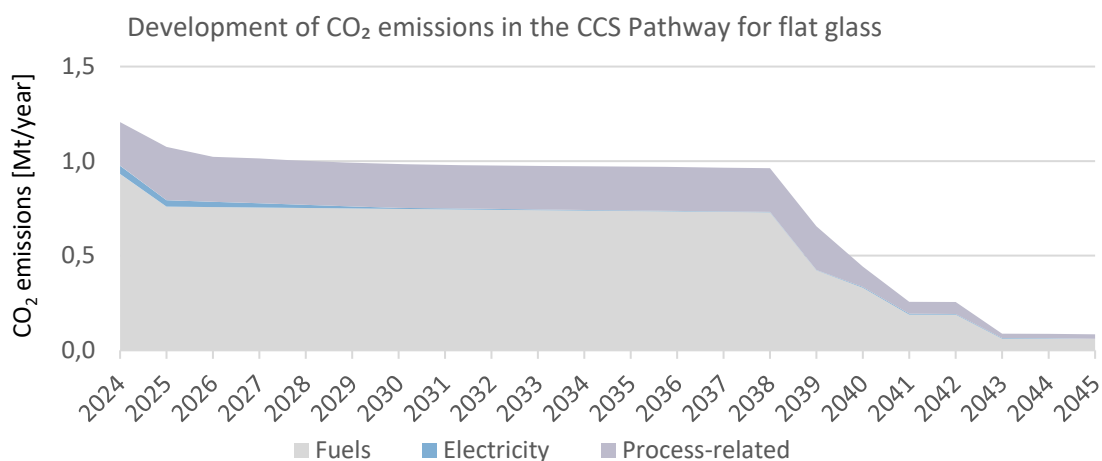


Figure 35 Development of CO₂ emissions in the CCS Pathway for flat glass production

Investment requirements

The CCS Pathway requires investments in both furnace technology and additional carbon-capture equipment **Figure 36**. Relevant components include the oxy-fuel furnace configuration, oxygen supply

and airflow handling, carbon-capture equipment, CO₂ treatment and compression, and the site-level connection to the assumed CO₂ transport infrastructure.

Cumulative investment requirements for flat glass amount to €0.648 billion by 2045. For comparison, cumulative investment requirements for flat glass in the Hybrid Pathway amount to €0.827 billion.

The BAU Pathway requires a different interpretation. Conventional furnaces also require replacement at the end of their technical lifetime, meaning that the BAU case is not investment-free. These investments represent baseline reinvestment to maintain production capacity, not additional transformation-related expenditure.

Within the defined model boundary, cumulative investment in the CCS configuration is therefore €0.04 billion lower than in the Hybrid Pathway. This difference should not, however, be interpreted as evidence that CCS is economically cheaper overall. The infrastructure costs included in the CCS Pathway represent modelling assumptions rather than project-specific cost estimates. Actual costs for oxygen supply, CO₂ conditioning, compression, connection to a transport network, transport, and geological storage will depend strongly on on-site location, transport distance, infrastructure utilisation, the size of the captured CO₂ stream, storage conditions, and the future development of shared CO₂ infrastructure.

Moreover, the investment values shown in Figure 32 do not include the full costs of developing a national or European CO₂ transport and storage net-

work. The model therefore captures only those infrastructure components and cost assumptions assigned to the production site within the defined system boundary.

The reported investment requirements should therefore be interpreted as scenario-based estimates within the roadmap's model boundary, not as a forecast of the actual total cost of deploying CCS at individual flat glass sites.

Operating expenditure also differs substantially between the configurations. CCS requires oxygen supply, carbon capture, CO₂ compression, transport, and storage, while the Hybrid Pathway depends strongly on future hydrogen and electricity prices and availability.

Therefore, interpret the investment results in **Figure 36** together with the specific abatement-cost development in **Figure 33**. Capital expenditure alone does not determine CCS economic viability.

^{42,43}

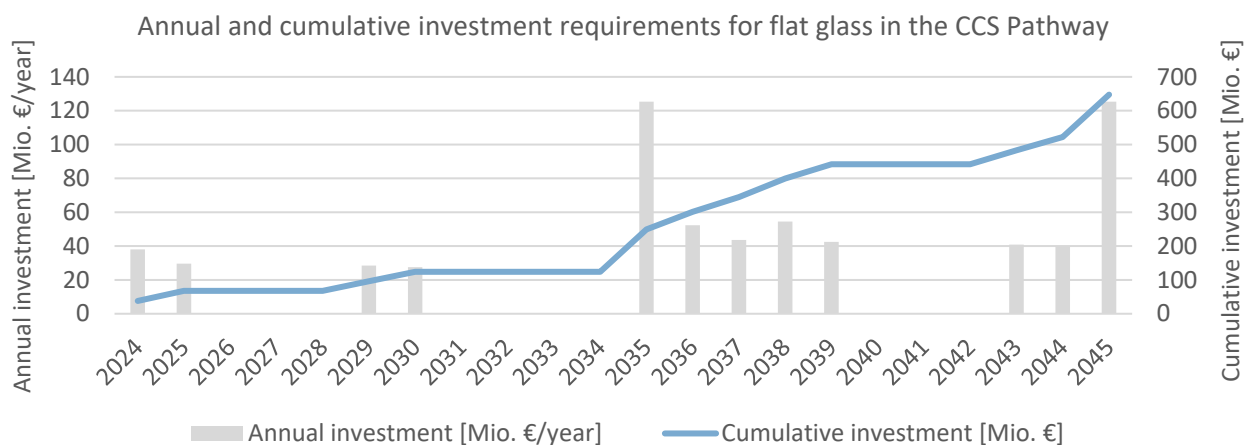


Figure 36 Required investments for flat glass in the CCS Pathway

Comparison and assessment of the BAU and Hybrid Pathways for flat glass

The role of CCS in flat glass production can be assessed against two benchmarks. The BAU Pathway represents continued conventional natural-gas-based production without structural decarbonisation of the furnace portfolio. The Hybrid Pathway represents the principal alternative transformation route, combining hydrogen and electricity in hybrid furnace configurations. All three pathways assume the same flat glass production capacity in 2045 but differ substantially in furnace technology, energy demand, emissions, infrastructure requirements and investment needs.

Table 10 summarises the main differences between the BAU, Hybrid and CCS Pathways for flat glass in 2045. The three pathways represent fundamentally different transformation strategies. The BAU Pathway retains conventional natural-gas-based production and consequently leaves both fuel- and process-related emissions largely unabated. The Hybrid Pathway follows an avoidance strategy: natural gas is eliminated by 2045 and replaced by hydrogen and electricity, substantially reducing fuel-related emissions while process-related emissions from carbonate decomposition remain. The CCS Pathway follows a capture strategy. Natural gas remains in use, but regenerative air-fired furnaces are replaced with oxy-fuel furnaces combined with carbon capture, allowing capture of both fuel-related and process-related CO₂ in the exhaust stream.

In the CCS Pathway, deployment begins in 2040. In 2040, approximately 0.874 Mt/a of flat glass production capacity converts to the oxy-fuel CCS configuration, rising to approximately 1.188 Mt/a in 2041 and 2042. From 2043 onwards, oxy-fuel furnaces with CCS represent the full 1.470 Mt/a of modelled flat glass production capacity. Until the transition begins, conventional regenerative cross-fired furnaces remain, avoiding an intermediate investment in a new hybrid furnace configuration shortly before CCS is assumed available.

In 2045, the CCS configuration requires approximately 10.2 PJ/a of natural gas and 1.13 PJ/a of electricity, corresponding to a total final energy demand of approximately 11.32 PJ/a. Residual emissions amount to approximately 0.084 Mt CO₂/a. Compared with the Hybrid Pathway (residual emissions of approximately 0.231 Mt CO₂/a), the CCS configuration reduces residual flat glass emissions by approximately 64%. A capture rate of 90% is assumed for the fuel- and process-related CO₂ streams of the CCS-equipped furnaces.

Cumulative plant-level investment in the CCS configuration amounts to approximately €0.648 billion by 2045, compared with approximately €0.69 billion in the Hybrid Pathway. This relatively small difference should not be interpreted as demonstrating an inherent cost advantage of CCS. The investment assessment excludes the full system-wide costs of future CO₂ transport and geological storage infrastructure, and operating costs also depend on oxygen supply, capture operation, CO₂ conditioning, transport, and storage.

CCS should therefore be understood as a conditional, site-specific decarbonisation option for large flat glass production sites, rather than a substitute for efficiency improvements, electrification, or fuel switching across the glass industry. Its viability will depend on furnace and site characteristics, the available and capturable CO₂ stream, access to transport and storage infrastructure, capture performance, future CO₂ prices and the cost and availability of competing transformation options.

Table 10 Comparison of the BAU, Hybrid and CCS Pathways for flat glass production in 2045.

2045	BAU – flat glass	Hybrid – flat glass	CCS – flat glass
Production capacity	1.470 Mt/a	1.470 Mt/a	1.470 Mt/a
Furnace configuration	regenerative cross-fired furnaces	H ₂ hybrid and H ₂ super-hybrid	natural-gas oxy-fuel + CCS
Number of conventional flat glass furnaces	10	0	0
Natural gas in melting	16.9 PJ/a	0 PJ/a	10.20 PJ/a
Hydrogen	0 PJ/a	9.77 PJ/a	0 PJ/a
Electricity	0.44 PJ/a	2.77 PJ/a	1.13 PJ/a
Total final energy demand	17.34 PJ/a	12.54 PJ/a	11.32 PJ/a
Residual CO ₂ emissions	1.16 Mt CO ₂ /a	0.231 Mt CO ₂ /a	0.084 Mt CO ₂ /a
Main residual emission sources	fuel- and process-related	predominantly process-related	uncaptured residual fuel- and process-related emissions
Carbon capture	no	no	yes
Main additional infrastructure	existing gas and electricity infrastructure	electricity and hydrogen infrastructure	oxygen supply and CO ₂ capture, transport and storage
Cumulative transformation investment	€0.459 billion	€0.827 billion	€0.648 billion

4.5 Overall Comparison

4.5.1 Contribution to the decarbonisation of the Glass industry

Figure 37 shows the development of annual CO₂ emissions across the pathways. Starting from total modelled emissions of 3.6 Mt CO₂/a in the BAU Pathway, this decline is primarily attributable to reduced modelled production capacity and the assumed decarbonisation of the electricity supply, rather than to a structural transformation of the furnace stock.

By contrast, the Electrification, Hydrogen and Hybrid Pathways each reduce total annual emissions to 0.492 Mt CO₂/a in 2045. This corresponds to an 86.5% reduction relative to the 2024 model baseline. All three pathways eliminate fuel-related fossil CO₂ emissions, and indirect emissions from electricity consumption reach zero, assuming a fully decarbonised electricity supply in 2045.

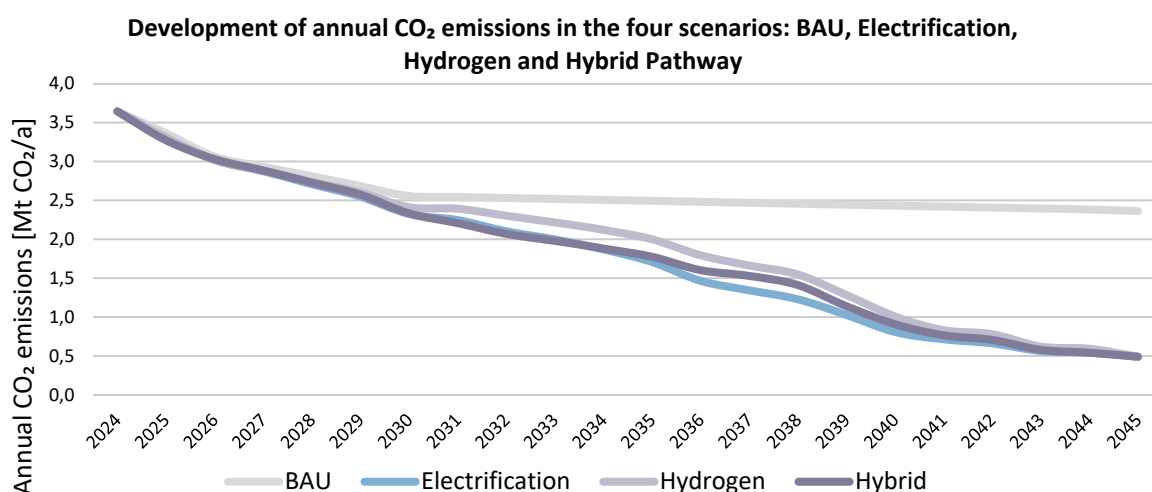


Figure 37 Development of annual CO₂ emissions in the four scenarios: Reference, Electrification, Hydrogen and Hybrid Pathway.

The remaining emissions are therefore almost entirely process-related and result from decomposing carbonate raw materials during glass melting. Consequently, the updated model no longer shows a meaningful difference in 2045 residual emissions between the Electrification, Hydrogen, and Hybrid Pathways. The comparative assessment should instead focus on technological feasibility, energy supply, infrastructure requirements, and economic implications.

The CCS Pathway reduces emissions further. In the current CCS scenario, total annual emissions decline to 0.344 Mt CO₂/a in 2045, a 90.6% reduction relative to 2024. Compared with the 0.492 Mt CO₂/a remaining in the other transformation pathways, CCS therefore reduces residual emissions by an additional 0.148 Mt CO₂/a, or 30%.

This additional reduction results from capturing both fuel-related and process-related CO₂ at the CCS-equipped flat-glass furnaces. We assume a 90% capture rate for these emission streams. However, CCS is introduced only from the late 2030s onwards, depending on the respective furnace-rebuild cycles. Its contribution to cumulative emission reductions over the complete modelling period is therefore smaller than the difference between the 2045 end-point values alone would suggest. None of the pathways achieve completely emission-free glass production within the model assumptions. Even with CCS, some residual emissions remain because capture is incomplete and CCS is not applied to hollow glass and technical glass. While the transformation pathways converge on the same residual-emission level in 2045, the timing of emission reductions over the modelling period differs.

4.5.2 Energy demand and infrastructure requirements

While the three main transformation pathways reach essentially the same residual emission level, they differ considerably in their future energy-carrier requirements. **Figure 38** compares the development of electricity and hydrogen demand.

The Electrification Pathway has the highest electricity demand, increasing from 8.1 PJ/a in 2024 to 26.0 PJ/a in 2045. Hydrogen demand remains at 7.3 PJ/a because the pathway retains highly electrified hydrogen-based hybrid furnaces where complete electrification is not assumed to become technically feasible, particularly in flat glass. The pathway therefore requires substantial expansion of site-level electrical infrastructure, including grid connections, transformers, switchgear, substations and internal distribution systems.

The Hydrogen Pathway has a fundamentally different supply profile. Hydrogen demand reaches 24.2 PJ/a in 2045, equivalent to 6.72 TWh/a or around 171,000 t H₂/a on a higher-heating-value basis. Electricity demand also increases to 14.5 PJ/a because hydrogen-based hybrid furnaces retain an electrical share and all-electric furnaces remain part of the technology portfolio. The pathway therefore depends most strongly on the future availability, transport and regional distribution of hydrogen. This represents a greater infrastructure risk than electricity supply, as electricity is already available at all production sites, although substantial grid reinforcement may be required.

The Hybrid Pathway combines both energy carriers. In 2045, electricity demand reaches 24.8 PJ/a and hydrogen demand 12.0 PJ/a, while natural gas is completely phased out. It therefore requires slightly less electricity than the Electrification Pathway but substantially more hydrogen. This also resolves the inconsistency in the previous model version, in which the Hybrid Pathway appeared to require more electricity than the Electrification Pathway.

The CCS Pathway reaches an electricity demand of approximately 23.1 PJ/a and a hydrogen demand of 2.2 PJ/a, while natural-gas demand amounts to 10.2 PJ/a in 2045. Compared with the Hybrid Pathway, the main difference is the replacement of the hydrogen-based flat-glass configuration with natural-gas-fired oxy-fuel furnaces equipped with CCS. Hydrogen remains in use in the hollow-glass and technical-glass segments.

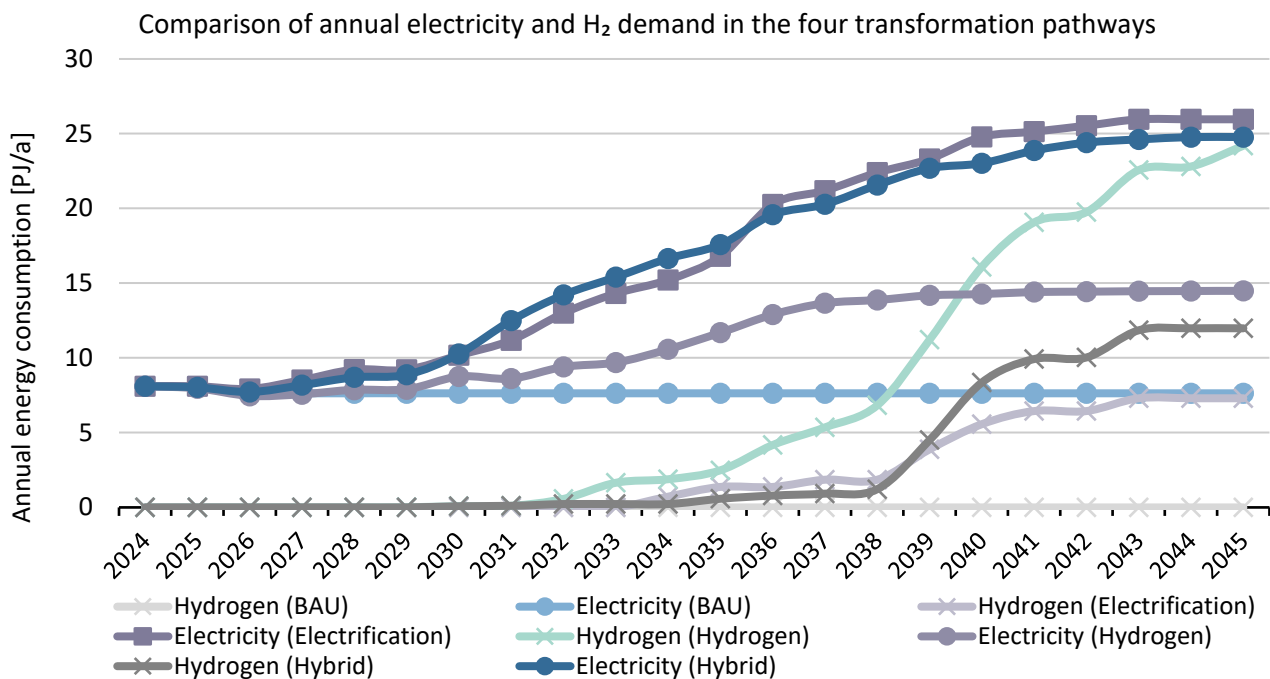


Figure 38 Comparison of annual electricity and H₂ demand in the four transformation pathways.

The resulting infrastructure requirements differ accordingly. Electrification primarily requires electricity-grid reinforcement, the Hydrogen Pathway depends most strongly on new hydrogen infrastructure, and the CCS Pathway additionally requires CO₂ capture, conditioning, transport and permanent geological storage. The Hybrid Pathway distributes its infrastructure dependence between electricity and hydrogen, although both systems must develop in parallel. The pathways also differ in total final energy demand because of differences in furnace technologies and energy efficiency. In 2045, final energy demand amounts to 33.3 PJ/a in the Electrification Pathway, 35.5 PJ/a in the CCS Pathway, 36.8 PJ/a in the Hybrid Pathway and 38.7 PJ/a in the Hydrogen Pathway. The BAU Pathway remains highest at 43.8 PJ/a.

The pathways also differ substantially in their cumulative investment requirements as shown in **Table 11**. The comparison follows a common plant-level system boundary covering furnace replacement or modification and technology-specific infrastructure within the production site up to the interface with external electricity, hydrogen or CO₂ infrastructure.

External transmission networks, hydrogen production and transport systems, CO₂ transport networks and geological storage capacity are excluded.

Table 11 Cumulative plant-level investment requirements by pathway up to 2045

Pathway	Cumulative plant-level investment 2045	Additional investment compared to BAU
BAU	€1.84 bn	–
Hydrogen	€3.76 bn	€1.92 bn
Electrification	€5.64 bn	€3.80 bn
CCS	€6.11 bn	€4.27 bn
Hybrid	€6.15 bn	€4.31 bn

The BAU Pathway requires cumulative investment of €1.84 billion by 2045, representing the baseline reinvestment required to maintain the production system. Among the three main transformation pathways, the Hydrogen Pathway has the lowest cumulative plant-level investment at €3.76 billion, corresponding to an additional €1.92 billion relative to BAU. The Electrification Pathway requires €5.64 billion, or €3.80 billion above BAU, while the Hybrid Pathway reaches €6.15 billion, €4.31 billion above BAU.

For comparison, annual investment in the three manufacturing branches most closely corresponding to the modelled glass segments averaged approximately €534 million between 2020 and 2024. The Electrification and Hybrid Pathways correspond to average annual plant-level investments of approximately €256 million and €280 million, respectively, over 2024–2045.⁴⁴ These values are not directly comparable, however, because the statistical data cover a broader range of assets and activities, while the pathway investments include baseline re-investment in production facilities.⁴⁴

The comparatively high cumulative investment in the Hybrid Pathway does not imply that individual hybrid furnaces are necessarily more expensive. Rather, it reflects the assumed sequence of technologies, furnace lifetimes and number of rebuilds over the modelling period.

The CCS Pathway reaches cumulative plant-level investment of €6.11 billion by 2045, only €0.04 billion below the Hybrid Pathway. This difference should not be interpreted as the stand-alone cost of CCS, because the CCS Pathway replaces the flat-glass technology configuration assumed in the Hybrid Pathway rather than adding capture equipment to an otherwise unchanged system.

For CCS, the plant-level boundary includes the oxy-fuel furnace configuration, site-level oxygen supply where required, flue-gas treatment and capture equipment, CO₂ purification, drying and compression or conditioning, and the internal connection to the CO₂ transfer point. External CO₂ transport and geological storage remain excluded.

Similar plant-level investment levels therefore do not imply similar total system costs. The Hydrogen Pathway is particularly exposed to future hydrogen prices, Electrification to electricity prices and grid requirements, Hybrid to the parallel development of electricity and hydrogen infrastructure, and CCS to natural-gas and oxygen costs, capture OPEX and CO₂ transport and storage charges. Therefore, as-

sess operating costs alongside investment requirements when evaluating the long-term economic viability of the pathways.

4.5.3 Overall Conclusions

Table 8 summarises the main results for the transformation pathways. The Electrification, Hydrogen and Hybrid Pathways all reduce total modelled emissions by 86.5% relative to the 2024 baseline and reach residual emissions of 0.492 Mt CO₂/a in 2045. Their main differences therefore lie in furnace technologies, energy carriers, infrastructure requirements and investment needs.

The Electrification Pathway achieves the lowest final energy demand at 33.3 PJ/a in 2045. Electricity demand reaches 26.0 PJ/a and hydrogen demand 7.3 PJ/a, as hydrogen-based hybrid furnaces remain necessary where complete electrification is not assumed within the modelling horizon. The pathway therefore depends particularly on sufficient grid capacity, reliable electricity supply and internationally competitive electricity prices.

The Hydrogen Pathway has the lowest cumulative plant-level investment requirement of the three main transformation pathways at €3.76 billion but creates the greatest dependency on hydrogen supply. Hydrogen demand reaches 24.2 PJ/a and electricity demand 14.5 PJ/a in 2045, resulting in total final energy demand of 38.7 PJ/a. The lower modelled CAPEX must therefore be considered alongside hydrogen infrastructure requirements and future operating-cost risks.

The Hybrid Pathway combines electricity and hydrogen, with 24.8 PJ/a of electricity and 12.0 PJ/a of hydrogen in 2045, while completely phasing out natural gas. Total final energy demand amounts to approximately 36.8 PJ/a. Cumulative plant-level investment reaches €6.15 billion, making the Hybrid Pathway the most investment-intensive of the three main transformation pathways. This reflects the assumed sequence of furnace technologies, lifetimes and rebuild cycles.

The CCS Pathway follows the Hybrid Pathway for hollow glass and technical glass, while replacing the hydrogen-based flat-glass configuration with natural-gas-fired oxy-fuel furnaces equipped with carbon capture. In 2045, the overall CCS Pathway requires approximately 23.1 PJ/a of electricity, 2.2 PJ/a of hydrogen and 10.2 PJ/a of natural gas, resulting in a total final energy demand of approximately 35.5 PJ/a. Modelled residual CO₂ emissions amount to 0.344 Mt CO₂/a, compared with 0.492 Mt CO₂/a in the other transformation pathways. The pathway continues to rely on natural gas and requires oxygen supply, CO₂ transport and permanent geological storage infrastructure. Cumulative plant-level investment amounts to approximately €6.11 billion.

Overall, the pathways imply different combinations of technologies, energy carriers and infrastructure

requirements, **Table 12**. Electrification is becoming increasingly important across the glass industry, while hydrogen remains relevant where full electrification is constrained. CCS provides an additional option for addressing residual process emissions in large-scale flat-glass production. Implementation ultimately depends on the timely availability of the required infrastructure and on operating conditions that allow German glass production to remain internationally competitive.

Table 12 Overall pathway comparison in 2045

Criterion	Electrification	Hydrogen	Hybrid	CCS
CO ₂ emissions 2045[Mt CO ₂ /a]	0.492	0.492	0.492	0.344
Total final energy 2045 [PJ/a]	33.3	38.7	36.8	35,5
Electricity demand [PJ/a]	26	14.5	24.8	23.1
Hydrogen demand [PJ/a]	7.3	24.2	12	2.2
Natural-gas demand [PJ/a]	0	0	0	10,2
Cumulative investment [€ bn]	5.64	3.76	6.15	6.11
Principal infrastructure dependency	Electricity	Hydrogen	Electricity + hydrogen	CO ₂ transport and storage
Main advantage	Lowest final energy demand	Lowest transformation CAPEX	Diversification of energy carriers	Lowest residual emissions
Main challenge	Grid capacity and electricity cost	H ₂ availability and cost	Parallel infrastructure requirements	CO ₂ infrastructure and CCS operating costs

5 Political and Regulatory Framework Conditions

The glass industry's transformation is not determined by technology alone. Its success depends largely on the political and regulatory framework that shapes companies' long-term investment decisions. In practice, decarbonisation pathways must be assessed not only for technical maturity, but also for funding availability, legal certainty, infrastructure rollout, electricity and hydrogen market conditions, trade-related carbon-leakage protection, and the future treatment of residual emissions. Since the first transformation roadmap for the glass sector, these framework conditions have become more concrete, but also more complex. Recent sector evidence underlines that furnace investment cycles remain long and site-specific, and that transition will require timely extension and reinforcement of both site-level and external infrastructure.⁴⁵

5.1 Funding Instruments and Legal Developments

Expanding industrial decarbonisation support instruments is an important element of the policy framework. In Germany, the Federal Funding for Industry and Climate Protection (BIK) entered into force in August 2024 as the successor to the former "Decarbonisation in Industry" programme and is intended to run until 2030. The programme supports investment as well as research, development and innovation projects for industrial decarbonisation and explicitly addresses energy-intensive industries including the glass industry. Under Module 1, Submodule 2, projects could receive funding of up to €200 million per beneficiary; this submodule expired at the end of 2025. Module 1 funding continues through the remaining funding categories.⁴⁵

Another instrument is the German Carbon Contracts for Difference scheme ("Klimaschutzverträge"). The first bidding round was launched in March 2024 with a funding volume of €4 billion. The

instrument supports climate-friendly industrial production by compensating for part of the additional operating-cost burden of low-carbon production processes over longer time horizons. This is particularly relevant for the glass industry because operating-cost differences between conventional and low-carbon production technologies can remain substantial even after the initial investment.⁴⁶

A further important development concerns the legal framework for carbon management. The Federal Government has advanced the legal basis for carbon capture, transport and storage in Germany. This is relevant for the glass industry because process-related emissions from carbonate-based raw materials remain even when energy-related emissions are substantially reduced. However, legal enablement alone does not ensure practical availability. Developing CO₂ transport and storage infrastructure can take several years, so infrastructure planning and plant-level investment decisions must be coordinated well in advance.⁴⁷

Carbon pricing and trade-related carbon-leakage protection constitute another relevant regulatory dimension. The EU Carbon Border Adjustment Mechanism (CBAM) has been in effect since 1 January 2026. Its current sectoral scope covers cement, iron and steel, aluminium, fertilisers, electricity and hydrogen, but not glass products. Consequently, CBAM currently provides no corresponding border-adjustment mechanism for glass products. The future interaction between EU ETS carbon costs, international competition and carbon-leakage protection therefore remains relevant for the competitiveness of European glass production.²²

Taken together, these developments show that the regulatory framework is increasingly being translated from broad long-term strategies into operational funding instruments, legal provisions and infrastructure planning. For the glass industry, this

creates new implementation opportunities but also increases the importance of aligning investment decisions with evolving regulatory and infrastructure conditions.

5.2 The Importance of Infrastructure Planning Security

Beyond funding and legal instruments, planning security is central to industrial decarbonisation. Glass furnaces are long-lived core assets, rebuild windows are infrequent, and continuous production leaves limited scope for short-term technological changes. Companies must therefore make technology and infrastructure decisions several years before a furnace rebuild. Uncertainty about electricity prices, hydrogen availability, carbon-cost exposure, or future support conditions can therefore delay investment decisions.²

The first key infrastructure dimension concerns hydrogen transport. The Federal Network Agency approved the German Hydrogen Core Network on 22 October 2024. According to the Bundesnetzagentur, the approved network comprises 9,040 km of pipelines, 60% of which are conversions of existing natural gas pipelines, with expected investment costs of €18.9 billion.¹⁶ For the glass industry, however, a national core network does not guarantee hydrogen availability at individual production sites. A specific plant's access to hydrogen depends on its location, regional connection infrastructure, the timing of network availability, and whether supply becomes available within the relevant furnace-rebuild window. Hydrogen should therefore be regarded as a strategically relevant but infrastructure-dependent option rather than as a universally available solution for the sector.¹⁶

The second infrastructure dimension concerns electricity supply and network tariffs. Electrification and highly electrified hybrid furnace concepts substantially increase plant-level electricity demand. At the same time, glass production is characterised by continuous thermal processes, high process inertia, and strict product-quality requirements, which limit short-term load flexibility. Electricity-market conditions therefore matter not only through average electricity prices, but also through grid-connection capacity, network charges and security of supply.^{5,48}

A third infrastructure dimension concerns CO₂ transport and storage. The Carbon Management Strategy makes clear that carbon management requires plant-level capture technologies, transport infrastructure, and access to storage, all available at the same time. Current analysis of the German situation underlines that legal enablement alone is insufficient if transport infrastructure is not developed in parallel. For the glass industry, this means CCS/CCU can only credibly complement residual process emissions if planning for CO₂ transport and storage proceeds alongside plant-level decarbonisation efforts.^{17,33,35}

Overall, the political and regulatory framework clearly shows that the glass industry's transformation will not fail because of a lack of viable technology options. Its success or failure will depend on whether policy creates a sufficiently predictable environment for long-term industrial investment. Funding instruments, legal reforms, hydrogen and CO₂ infrastructure, electricity-market conditions, and regulatory stability are therefore not secondary context variables. They are core conditions to implement the decarbonisation pathways discussed in this roadmap.

6 Outlook and Recommendations

The glass industry's target is clear and set by European, National, and regional climate targets: carbon neutrality by 2045/2050. However, the pathway to achieve this transformation is more uncertain and offers different approaches. The pathway analysis for the German glass industry presented in this roadmap study shows that deep decarbonisation is achievable. However, the transformation will neither occur autonomously nor follow a uniform technology transformation route. Instead, transformation steps will depend on a differentiated combination of electrification, hydrogen-based solutions, hybrid furnace concepts, circularity measures, raw-material strategies and, where necessary and feasible, carbon capture options. Pathways will not stand on their own but are embedded in overall developments in other sectors of industry, the energy industry, and overall energy and climate policy in Germany and the EU. The pathway also does not forecast the glass industry's future development but analyses potential transformation pathways.

The roadmap distinguishes between hollow glass, flat glass, and technical and other glass. It does not quantify or address glass-fibre production, flat-glass finishing or other downstream finishing steps. Keep this scope definition in mind when comparing the roadmap results with sector statistics. Differences will remain because the scopes differ. The roadmap focuses on the key products and the majority of the sector's energy consumption and emissions.

The decisive barriers to selecting decarbonisation technologies are not only technology-based; they also depend on the interaction of long-lasting furnace assets, limited rebuild windows, site space requirements, dependence on external infrastructure, capital intensity and availability, energy-price exposure, regulatory uncertainty, and international competition. Whether a furnace concept becomes an investable industrial option depends largely on

the external framework the glass industry cannot control.

The updated investment estimates underline the scale of the transformation challenge. These values are model-based estimates. Actual capital requirements may be higher, particularly where construction and material costs, site-specific infrastructure needs and implementation risks exceed the assumptions reflected in the model. First-of-a-kind plants also face higher capital costs. But capital expenditures alone do not determine economic viability. Operating costs, energy prices, grid charges and the cost of low-carbon energy carriers remain decisive for investment decisions. Every investment requires a business case.

Against this background, the roadmap is not defining a single blueprint for the transformation. Instead, it identifies a differentiated solution space and derives strategic implications for industry and policymakers.

6.1 Key Results

The German glass industry is highly heterogeneous. Hollow glass, float glass, and technical and other glass differ substantially in furnace size, process conditions, product-quality requirements, production structure, market conditions, and customer segments. Decarbonisation strategies must therefore reflect segment-specific and site-specific conditions rather than rely on a single generic sector model based on average data. The analysis in this Roadmap for the German Glass industry is based on a site-by-site basis.

Electrification becomes increasingly important across all transformation pathways. However, feasibility depends on furnace size, product requirements, grid-connection capacity, electricity prices, and the maturity of relevant technologies. In particular, assess the transferability of furnace concepts

with high shares of electric melting cautiously for large float-glass applications. Recent pilot projects in the glass industry demonstrate technological progress, but industrial-scale validation is outstanding.

Hydrogen remains a relevant but selective option.

Its role will depend on the availability of the required Hydrogen infrastructure, significant future price reductions, furnace concepts and product-specific requirements. Hydrogen cannot be treated as a universal drop-in solution for the entire sector, even though limited adaptation requirements at production sites make it look attractive.

Hybrid furnaces may become a central component of a differentiated, flexible transformation strategy.

Hybrid solutions typically balance efficiency with risk mitigation. They help gradually reduce emissions, preserve technological options, and provide flexibility if other developments come late, go in different directions, or may not happen at all. They will typically require at least some double investment in infrastructure to achieve this flexibility.

Process-related emissions important for near zero glass production.

Process emissions arise primarily from the decomposition of carbonate-based raw materials applied for glass melting and cannot be eliminated by switching to low-carbon energy carriers. Consequently, process-related emissions are directly coupled to the residual CO₂ emissions in the Electrification, Hydrogen and Hybrid Pathways in 2045. Their amount is directly linked to the amount of raw materials melted.

Circularity measures, such as increased cullet use and raw-material innovation to reduce the required amount of carbonates, can help reduce residual process emissions. Still, material availability, quality requirements, and segment-specific limitations constrain their overall potential savings. Circularity measures are no-regrets for the industry, but the challenges of collecting, sorting, and treating waste glass should not be underestimated. Especially for very high-quality glass (e.g., flat glass), the share of external cullet that can be used is limited.

CCS or CCU can reduce residual process emissions.

Applying CCS/CCU in the glass industry should focus on large production sites, where the specific cost of CO₂ avoidance is lower. If only process emissions remain, the specific cost will be high because each site has limited residual emissions. We therefore examined CCS/CCUS only for float-glass sites from 2040 onwards. Currently, Germany has neither CO₂ pipeline infrastructure nor a storage site. Train or ship transport of CO₂ may be available as an interim solution but will incur high operating costs. Planning for a first CO₂ Backbone has started but will likely take 10 to 15 years before CO₂ infrastructure becomes available.

Transformation must be discussed in the context of strained economic conditions and international competition.

Germany's glass industry is strategically important, providing products essential for packaging (pharmaceuticals, food and beverages), buildings, energy-related applications, transport, security and defence, as well as for digital infrastructure and technologies, including data centres and AI applications. Therefore, preserving domestic production capacity should not only be an economic objective but an industrial and resilience-policy priority.

6.2 Recommendations for Policymakers and the Glass Industry

The updated pathway analysis confirms that the glass industry's decarbonisation will not follow a single technology pathway. The appropriate transformation route depends on site- and plant-specific conditions, furnace-rebuild cycles, subsector-specific technical constraints, energy-carrier and infrastructure availability, and economic viability.

Electrification is expected to play a central role across the transformation pathways, while hydrogen is likely to remain more selective and dependent on local conditions. Hybrid concepts can offer a robust transition option amid uncertain infrastructure and energy-price developments, though their operational flexibility should not be overstated. At

the same time, fuel switching alone cannot eliminate process-related emissions, making circularity, alternative raw materials, and potentially CCS/CCU relevant complementary measures.

The transformation therefore requires coordinated action by policymakers and industry, combining technological development with reliable infrastructure, competitive energy costs, investment security, and measures to address residual emissions.

6.2.1 Recommendations for Policymakers

Policy support should reflect the operational and economic realities of glass production, including continuous operation, site-specific furnace-rebuild cycles, limited short-term flexibility and the importance of energy and CO₂ costs for international competitiveness. Against this background, the following policy priorities emerge from the Roadmap analysis:

1. Prioritize infrastructure rollout and plan security as a key requirement for the transformation.

For the glass industry, as for other high-temperature process industries, infrastructure is a precondition for transformation. The roadmap shows that infrastructure availability timing will likely be as decisive as the technological maturity of furnace concepts. Many future investment decisions will depend on whether a site can secure additional electrical grid-connection capacity and, where relevant, access to the future hydrogen network, when a furnace replacement becomes due. Rebuild windows occur periodically, but their timing is site-specific and cannot be calculated by a uniform furnace-lifetime assumption. Extending furnace lifetime is sometimes possible but increases operational costs and accident risk. If companies lack clarity on infrastructure availability before making investment decisions, they are likely to defer action, favour lower-risk conventional solutions, or even close the plant. Policymakers should therefore treat electricity-grid expansion, grid-access regulation, industrial connection upgrades, and transparent communication of infrastructure development timelines as strategic

instruments of decarbonisation policy, not background conditions.

2. Design electricity-market conditions in line with the operational reality of the sector.

In broader debates on industrial electrification, the glass industry is often seen as a sector that could respond flexibly to electricity-market signals, like less process-constrained loads. However, this is not the case. Even hybrid furnaces have only insignificant short-term flexibility for fuel switching. Changes in furnace operation require long adjustment and transition periods. The glass sector therefore has only negligible potential to respond to short-term electricity price signals. The ongoing reform debate on individual industrial grid tariffs under Section 19(2) of the StromNEV is therefore highly important for the sector. Future rules should create system-compatible incentives without penalizing structurally continuous, inflexible demand that cannot be changed or shifted on short notice.

3. Review electricity-price components, grid charges, and regulatory requirements

If electrification is to become the backbone of industrial decarbonisation in the glass industry, electricity-market design must support, not penalize, continuous electricity demand. Policymakers should review electricity-price components, grid charges, and incentive structures with explicit regard to the glass sector's operating reality. Otherwise, technically feasible electrified and hybrid furnace concepts that reduce fossil fuel use may remain commercially unattractive even when strategically desirable.

4. Provide stable, long-term, and sufficient funding for the transformation

Industrial transformation in the glass sector is capital-intensive, time-sensitive, and closely linked to furnace-replacement cycles. Funding policy must be designed around industrial asset dynamics rather than short administrative funding windows alone. Existing instruments such as the Federal Funding for Industry and Climate Protection (BIK) recognize electrification, renewable hydrogen, and, in the

wider funding architecture, carbon-management-related measures as relevant transformation options. However, investment support alone will not be sufficient where low-carbon production routes create a persistent operating-cost gap. Policymakers should ensure support instruments are sufficiently predictable, avoid excessive bureaucratic burdens and long decision times, and align with the glass industry's investment cycles, addressing both capital expenditure and operating-cost risks. This is particularly important for the industrial-scale rollout.

5. Treat hydrogen as a strategic but selective pillar of policy, not as a universal solution for decarbonisation

Hydrogen should remain on the policy agenda, but evidence from the glass sector suggests its role in the industry will likely be highly differentiated. Infrastructure access, application-specific suitability, subsectoral differences, and cost will strongly influence hydrogen uptake in the glass industry. Policymakers should avoid treating hydrogen as a no-regret or drop-in solution. Technically demanding applications such as flat-glass production may be less likely to move quickly toward hydrogen-based operation than hollow-glass or other applications. Policy should therefore support hydrogen where site conditions, subsector characteristics, product requirements, and realistic infrastructure timelines make its use plausible, while avoiding expectations that may lead firms to rely on infrastructure or supply assumptions that do not materialize in time.

6. Support hybrid concepts as transitional and risk-mitigating solutions

In a transformation process characterized by uncertain infrastructure timing, uncertain future energy prices, and long-lasting industrial assets, the most robust pathway is not the one with the highest immediate decarbonisation potential. In many cases, a staged transition can be more credible, robust and investable than an immediate switch to a single decarbonized energy carrier. Hybrid furnace concepts can preserve optionality by allowing companies to increase electricity shares and decarbonisation over

time and, in some configurations, retain compatibility with later adoption of hydrogen. Do not dismiss hybrid configurations as insufficient solutions, and do not overstate operational flexibility. Hybrid concepts may serve as a bridge and remain a long-term complement where full electrification is not technically feasible.

7. Develop a dedicated policy package for residual process emissions

Even under ambitious electrification and hydrogen scenarios, fuel switching alone does not reduce process-related emissions from carbonate raw materials. Achieving net-zero emissions in the glass industry therefore includes higher cullet shares and the use of alternative or pre-calcined raw materials. However, cullet availability, quality, purity requirements, and product-specific limitations constrain these levers, especially in flat glass and technical glass production. They can reduce residual emissions but not eliminate them. CCS and/or CCU should therefore be envisaged as complementary options. Transformation planning should address residual process emissions as an integrated part of the process, not as a last step after decarbonising the energy supply.

8. Strengthen circularity policy as a core decarbonisation instrument

Higher cullet use remains an important cross-cutting decarbonisation lever because it reduces both the energy required for melting and the amount of carbonate raw materials entering the process. Circularity policy should be treated as part of industrial climate policy, not waste policy. However, the potential to increase the cullet share is limited. Collection volumes, sorting quality, contamination levels, colour requirements, product specifications, and regulatory constraints limit the increasing uptake. These limitations are particularly relevant for flat and special glass; certain high-purity or regulated product streams, including some pharmaceutical applications, cannot use cullet or higher cullet shares for glass production. Policymakers should support collection (especially from the building sector), remelt-oriented sorting, quality assurance,

and improved sorting technologies, while recognizing segment-specific limits.

9. Protect competitiveness and avoid decarbonisation by deindustrialization

The glass industry competes in international markets and remains vulnerable to carbon leakage if energy and regulatory costs rise in Germany and the EU. If low-carbon production routes raise production costs without adequate measures to safeguard competitiveness, production may shift to other countries or regions, without reducing global emissions.

The Carbon Border Adjustment Mechanism (CBAM) does not currently cover glass products. Extending CBAM to glass under its current design would not effectively protect the sector from carbon leakage. In particular, the mechanism only addresses imports into the EU but does not provide equivalent protection for European glass manufacturers competing in export markets. As a result, including glass products in CBAM under the current framework would not adequately safeguard the international competitiveness of the European glass industry. Any future consideration of CBAM for glass would require a comprehensive approach that addresses both import and export competition and the relevant cost disadvantages faced by German and European producers.

Policymakers must therefore maintain and further develop effective carbon-leakage safeguards for the glass industry, including competitive electricity prices, appropriate grid charges for energy-intensive industries and adequate electricity-price compensation. A successful glass policy must combine climate ambition with industrial competitiveness.

10. Expanding markets for low-carbon glass products

Investment support will not be sufficient for the transformation, if low-carbon glass production remains more expensive compared to conventional production. The economic viability of investments in low-carbon production technologies depends on

customers who are willing to bear the additional costs of decarbonisation to contribute to overall climate targets. Market conditions, customer requirements and competitive pressures vary considerably across glass segments.

Policymakers should support transparent, reliable frameworks for assessing and communicating the carbon footprint of glass products, while allowing sector-specific and market-based approaches. Voluntary initiatives and value-chain cooperation can help strengthen demand for low-carbon glass products. Any potential demand-side policy instruments should be developed in close consultation with the affected industry segments. Demand-side policy instruments are best suited for products where demand is driven by public procurement, such as building glazing. Mandatory purchasing requirements are typically distorting markets

Creating favourable market conditions or creating demand by public procurement can improve the commercial viability of low-carbon glass production and complement investment support without prescribing uniform demand-side obligations across the industry.

11. Accelerate permitting, coordination, and implementation procedures

The pace of industrial transformation depends not only on technology and finance but also on time constraints from relatively fixed reinvestment cycles. Slow approval processes for electricity connections, grid operators' capacity commitments, and approvals for site modifications, industrial construction, hydrogen infrastructure, or CO₂ transport integration can undermine decarbonisation plans even when funding and technology are available. Especially in sectors such as glass, where furnace rebuild timing offers little flexibility, timely decisions matter. Policymakers should improve coordination and accelerate permitting for industrial transformation projects. In practice, lost permitting time can be as damaging as missing funding because both can miss a rebuild cycle and lock in another decade of emissions.

12. Support for Pilot- and Demonstration Plants

The technology portfolio for glass decarbonisation is advancing, but large-scale implementation and commercialisation still need improvement. Technically demanding segments such as flat glass continue to require large-scale validation under real industrial conditions. Recent developments, including the inauguration of the Volta reduced-carbon flat-glass production line, show progress but do not prove full commercial readiness.¹³

Policymakers should continue supporting pilot and pre-commercial demonstrations, especially where technical uncertainty, quality requirements, and scale effects remain significant. Public support should not be limited to the largest emitting sectors, such as steel, cement, or the chemical industry; industries with residual process emissions should have access to suitable demonstration and scale-up instruments.

13. Treat the glass industry as a strategic sector in industrial transformation

Recognize the glass industry as a strategic supplier to low-carbon value chains. Its products support circular packaging systems, high-efficiency glazing, and a range of downstream climate-related applications. A glass roadmap should therefore be embedded in broader industrial, energy, infrastructure, and circular-economy strategies. The sector should not be treated as a marginal decarbonisation case but as part of the strategic core of industrial climate policy.

6.2.2 Recommendations for the glass Industry

For industry, the revised pathway assessment leads to an overall conclusion: the coming phase of transformation will depend less on commitment to a particular technology than on the quality of site-level preparation. The realism of pathway assumptions and the ability to align investment decisions with infrastructure availability, market conditions and furnace-rebuild cycles will be critical.

The updated modelling suggests a more selective role for hydrogen than previously assumed, without

removing it from the strategic technology portfolio. At the same time, electrification cannot be expected to advance uniformly or at the same pace across all sites and subsectors. Companies will therefore need differentiated transition strategies: broad electrification where technically and economically viable, selective hydrogen use where infrastructure and process conditions favour its deployment, and hybrid approaches where they provide a robust response to technological, infrastructure and market uncertainty. Hybrid concepts may serve as a staged transition option, but may also remain a long-term solution where full electrification is technically or economically constrained.

Companies must therefore not only identify a preferred long-term decarbonisation technology, but also develop implementation strategies that remain viable under different energy-price scenarios, changing policy conditions, evolving infrastructure timelines and the practical constraints of plant operation. The following recommendations translate strategic decarbonisation targets into investable and operationally credible transformation pathways.

1. Align transformation planning with furnace lifetime and rebuild windows

For glass manufacturers, relevant decision points are not evenly distributed over time. They cluster around rebuild cycles and major reinvestment decisions. Companies should treat upcoming furnace rebuilds as strategic transformation windows rather than as purely technical maintenance events. This requires much longer planning lead times, including early evaluation of infrastructure conditions, grid capacity connection needs, future product requirements, site-specific decarbonisation options, and the compatibility of alternative furnace concepts with plant layout and production strategy, including consequences for upstream and downstream processes. In practical terms, a technically attractive option has limited strategic value if it cannot be implemented when a rebuild is due. Timing and preparedness are central elements for success.

2. Develop site-specific pathways instead of uniform corporate narratives

A one-size-fits-all decarbonisation plan will not reflect the transformation realities of most glass companies. Conditions vary substantially across production sites by subsector, furnace size, product specification, available space, existing energy infrastructure, and location relative to future hydrogen or CO₂ pipeline routes. Companies should develop and prepare for differentiated site-level strategies that identify which plants are likely candidates for deep electrification, which may move through staged hybrid configurations, and where hydrogen may become relevant once external availability is secured. The more heterogeneous the company's furnace stock, the more important differentiated planning becomes.

3. Accept electricity as a core component of corporate decarbonisation strategy

Under the updated pathway assumptions, electricity is no longer a peripheral auxiliary input in decarbonisation planning. It becomes a central production factor in its own right. Companies should therefore move electricity planning to the core of their industrial strategy. This includes detailed analysis of future load development, site-specific connection capacity planning, backup and security-of-supply strategies, interactions with existing on-site systems, procurement strategies, and the technical implications of increasing electricity shares in melting. Barriers to increased electricity use extend beyond power prices; they also include grid connection costs, equipment lead times, network upgrades, and the operational consequences of unplanned supply interruptions. Firms that treat electricity as an afterthought risk discovering too late that they can't implement their preferred pathway.

4. Develop flexibility strategies in response to upcoming grid regulation.

In the past, near-constant consumption profiles earned lower grid charges. As renewable generation grows, the regulatory framework is increasingly expected to emphasize flexible rather than stable consumption patterns. However, glass production's

technical flexibility potential remains limited. Companies should therefore identify genuinely feasible flexibility options without compromising product quality, furnace stability, or efficiency. Hybrid concepts, storage solutions, and selected auxiliary processes may offer limited flexibility. The specific implications of the electricity-market reform for the glass industry require continued assessment.

5. Hybrid concepts as strategic bridge to a decarbonised but uncertain future

Hybrid concepts offer strategic flexibility while reducing emissions. When electricity and hydrogen availability and prices remain uncertain, hybrid approaches let firms act early without fully foreclosing other options. For companies that lack enough certainty to commit fully to a single technology choice but do not want to postpone decarbonisation until uncertainty disappears, hybrid concepts can bridge the gap. Companies should evaluate hybrid concepts not merely as technical compromises, but as strategic solutions that reduce lock-in and align better with real-world investment conditions. The most robust pathway may not be an immediate switch to full decarbonisation, but one that keeps future options open while still delivering progressive decarbonisation.

6. Assess hydrogen selectively, realistically, and in relation to plant-specific conditions

Hydrogen remains strategically relevant, but it is unlikely to become universally available at all sites at an affordable cost. Its role will depend heavily on on-site location and proximity to hydrogen infrastructure. Assess the hydrogen option against realistic assumptions rather than treating it as a generic placeholder or drop-in decarbonisation solution. Evaluate whether hydrogen availability aligns with planned rebuild cycles, whether the production process can accommodate hydrogen-based operation, and whether electrification or staged hybridization may provide a more robust route.

7. Integrate circularity and raw-material strategy into core transformation planning

The roadmap should not be read as a furnace technology roadmap alone. Instead, companies should incorporate circularity and raw-material strategy directly into their transformation planning. Higher cullet shares, stronger partnerships for collection and sorting, substitution of selected raw materials, and material-efficiency improvements can reduce both energy demand and process emissions. Their contribution is strategically valuable. Circularity and raw-material changes should be seen as important contributors, not a complete solution for process emissions.

8. Prepare for residual-emission management

Currently, the glass industry is not strongly engaged in CCS and/or CCU. However, this will become necessary when residual process emissions must be addressed. As electrification and other energy-related decarbonisation measures advance, the strategic importance of reducing process emissions will increase. Understanding the magnitude, composition, and reducibility of these emissions, the applicable technologies, and the extent to which they can be lowered through cullet, raw-material innovation, or process adaptation is important, even if final decisions on carbon management are not to be taken within the next five years. This will prevent future blind spots and improve long-term preparedness.

9. Participate actively in (collaborative) demonstration and sectoral learning

Decarbonisation in glass manufacturing is moving beyond conceptual stages, but industrial learning remains highly valuable, especially in applications where technical uncertainty and risks are still substantial. Collaborative R&D, pilot testing, pre-commercial scale-up, and cross-company knowledge exchange are particularly important in technically demanding segments such as large-scale flat glass production. The glass industry should strengthen its engagement to gain experience with CCS/CCU. Carbon-management solutions in the steel and cement industry are more advanced and focus on process- and energy-related emissions. Early en-

gagement can help clarify technical integration, infrastructure requirements, and the potential costs of carbon management solutions.⁴⁹

10. Improve internal data quality and decision support at plant level

A practical lesson from the roadmap process is that pathway plausibility depends heavily on the quality of plant-level information. This includes internal data on furnace age and condition, rebuild planning, energy demand, site-specific infrastructure constraints, cullet use, process-emission profiles, and product-related technical limitations. Better internal data improves not only the quality of strategic decision-making, but also the credibility of funding applications, the robustness of corporate transition planning, and the quality of future sectoral roadmap updates. In a sector transformation process shaped by site-specific constraints, weak data quickly erodes the roadmap's value.

11. Build transition strategies that remain robust under uncertainty

The next phase of glass decarbonisation will not be characterized by certainty and transparency on prices, infrastructure, or policy. Waiting for uncertainty to disappear is likely not an option; instead, develop credible strategies that combine technological ambition with optionality, identify no-regret measures, sequence larger investments carefully, and avoid pathway assumptions that depend on highly optimistic external developments. In the current context, robustness may be more valuable than apparent technological purity.

6.2.3 Possible Next Steps

The roadmap for Germany's glass industry has highlighted possible steps for the sector transition. Because the conditions will remain dynamic for many years, electricity prices, hydrogen availability, infrastructure build-out, policy support schemes, and the maturity of large-scale decarbonisation technologies will all continue to evolve. The sector's relevant question, therefore, is not whether uncertainty will disappear, but how to make decisions that remain trustworthy as conditions change. This

is precisely where the roadmap can be used: not as a prediction about the industry's future or a fixed blueprint, but as a structured decision-support framework for navigating transformation under uncertainty.

A priority is to further strengthen site-level transformation planning.

Although the Roadmap analysed possible site-level transformation pathways, it presents results only as an Overall outcome. It will be necessary to regularly confirm site-level assumptions, especially for sites approaching relevant rebuild or reinvestment windows. This includes, for example, directly requesting additional grid connection capacity from the grid operator or discussing cullet use. Site-level transformation planning must also include the transformation of downstream and auxiliary processes that might create additional electricity demand to be met.

A second focus should be closer alignment of general infrastructure planning and development. Infrastructure and industrial decision-making cannot be treated as separate processes. If connection upgrades, grid expansion, hydrogen rollout, or carbon-management infrastructure advance on timelines that do not match industrial rebuild cycles, the result may be delayed investment or lock-in rather than accelerated transformation. Future work should place greater emphasis on identifying timing mismatches between industrial demand and infrastructure delivery.

A third priority concerns demonstration and validation in technically challenging applications.

While the strategic direction is becoming clearer, uncertainties remain. Future roadmap updates can hopefully incorporate new evidence from ongoing transformation projects. Treat demonstration projects as an empirical learning base, not proof that all concepts are already market-ready across segments and scales. This matters because credible evidence on operational performance, product-quality stability, cost, and infrastructure implications can reduce

uncertainty far beyond the individual host site where testing is taking place.

A fourth priority is to further integrate residual-emission management into the roadmap. Earlier phases of sectoral decarbonisation are often dominated by energy- and fuel-related questions, because these are the most visible and immediate dimensions of transformation. However, as pathway assumptions become more concrete and electrification advances, the remaining process-emission challenge gains importance. Future roadmap development should therefore connect cullet, raw-material innovation, and carbon management more explicitly.

A fifth priority is methodological: future roadmap iterations should continue to improve plant-level data quality and pathway granularity, including existing site development planning. Broad directional narratives remain necessary, but are no longer sufficient to drive decarbonisation. Better information on remaining furnace lifetime, energy use, technical constraints, infrastructure exposure, and transition pathways will make results more robust. More granular site data will not eliminate uncertainty in the boundary conditions, but it will improve the quality of decisions taken under uncertainty. The German glass roadmap is entering a more implementation-oriented phase. The earlier task was to identify the principal technological options available for a hard-to-abate sector. The emerging task is more demanding: understanding how, where, and under what conditions these options can be implemented in practice. The updated roadmap, in which electrification becomes more central, hydrogen more selective and infrastructure-dependent, and hybrid solutions more strategically relevant as bridging technology or as longer-term complements in selected applications, is preparing for this next step. Circularity and residual-emission management are becoming more important to complete the route to climate neutrality.

List of Figures

Figure 1	High-voltage grid (110 kV) in Germany (2021), extended by the locations of German glass plants (red lines = congestion areas). ^{10,16,27–29}	28
Figure 2	Planned hydrogen network in Germany for 2030 (left) and 2050 (right). ^{32,33}	29
Figure 3	Planned CO ₂ pipeline network in Germany in 2032.	29
Figure 4	Projected development of end-user prices for natural gas, electricity and hydrogen, as well as CO ₂ allowance prices from 2024 to 2045. ^{31,40,41}	31
Figure 5	Development of energy consumption in the BAU Pathway	34
Figure 6	Development of CO ₂ emissions in the BAU Pathway	35
Figure 7	Annual and cumulative investment in the BAU Pathway	35
Figure 8	Development of production capacities by technology in the Electricity Pathway	36
Figure 9	Development of energy consumption in the Electrification Pathway	37
Figure 10	Development of CO ₂ emissions in the Electrification Pathway	38
Figure 11	Required investments in the Electrification Pathway	39
Figure 12	Development of production capacities by technology in the Hydrogen Pathway	40
Figure 13	Development of energy consumption in the Hydrogen Pathway	41
Figure 14	Development of CO ₂ emissions in the Hydrogen Pathway	42
Figure 15	Required investments in the Hydrogen Pathway	42
Figure 16	Development of production capacities by technology in the Hybrid Pathway	44
Figure 17	Development of energy consumption in the Hybrid Pathway	45
Figure 18	Development of CO ₂ emissions in the Hybrid Pathway	46
Figure 19	Annual and cumulative investments required for the implementation of the Hybrid Pathway in the German Glass Industry.	46
Figure 20	Distribution of production capacities by technology in the hollow glass sector in the Hybrid Pathway.	47
Figure 21	Development of energy consumption in the hollow glass sector in the Hybrid Pathway. ..	48
Figure 22	Development of CO ₂ emissions in the hollow glass sector in the Hybrid Pathway.	49
Figure 23	Required investments in the hollow glass sector in the Hybrid Pathway.	49
Figure 24	Distribution of production capacities by technology in the flat glass sector in the Hybrid Pathway.	51

Figure 25	Development of energy consumption in the flat glass sector in the Hybrid Pathway.	52
Figure 26	Development of CO ₂ emissions in the flat glass sector in the Hybrid Pathway.	52
Figure 27	Required investments in the flat glass sector in the Hybrid Pathway	53
Figure 28	Distribution of production capacities by technology in the technical glass sector in the Hybrid Pathway.....	54
Figure 29	Development of energy consumption in the technical glass sector in the Hybrid Pathway.	55
Figure 30	Development of CO ₂ emissions in the technical and other glass sector in the Hybrid Pathway.	55
Figure 31	Required investments in the technical and other glass sector in the Hybrid Pathway.....	56
Figure 32	Development of production capacities for flat glass in the CCS Pathway.....	58
Figure 33	Assumed development of CCS abatement costs for large flat-glass sites, 2024–2045.....	59
Figure 34	Development of energy consumption for flat glass in the CCS Pathway	60
Figure 35	Development of CO ₂ emissions in the CCS Pathway for flat glass production	61
Figure 36	Required investments for flat glass in the CCS Pathway	62
Figure 37	Development of annual CO ₂ emissions in the four scenarios: Reference, Electrification, Hydrogen and Hybrid Pathway.....	64
Figure 38	Comparison of annual electricity and H ₂ demand in the four transformation pathways.	66

List of Tables

Table 1 Key results of the transformation pathways in 2045	2
Table 2 Main characteristics and infrastructure requirements of the transformation pathways	3
Table 3 Cumulative plant-level investment requirements up to 2045 by pathway.....	3
Table 4 Priority actions for policymakers and the German glass industry	5
Tabelle 5 Zentrale Ergebnisse der Transformationspfade im Jahr 2045.....	8
Tabelle 6 Zentrale Merkmale und Infrastrukturbedarfe der Transformationspfade.....	9
Tabelle 7 Kumulierte Investitionsanforderungen auf Standortebeine bis 2045.....	10
Tabelle 8 Zentrale Handlungsfelder für die Politik und die deutsche Glasindustrie	12
Table 9 Expected development of the number of installed melting furnaces by sector in the BAU Pathway	33
Table 10 Comparison of the BAU, Hybrid and CCS Pathways for flat glass production in 2045.	64
Table 11 Cumulative plant-level investment requirements by pathway up to 2045.....	66
Table 12 Overall pathway comparison in 2045	68

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8 Annex

8.1 Assessment of the Current Status

A realistic update of the transformation pathways requires a robust understanding of the German glass industry's current status. For this reason, the roadmap relies not only on general sector assumptions but also on structured site-level data collection, project-based evidence, industry information, and comparative technical studies. This chapter therefore describes the sector's current state in a way that is sufficiently differentiated to support later scenario development. This includes the industry structure, the status of site-level technologies and emissions, the available infrastructure context, and the current landscape of ongoing research and development activities. Existing German and international sector studies consistently show that such differentiation is necessary because the glass industry cannot be understood as one uniform process system, but rather as a set of technically and economically heterogeneous production environments.

8.1.1 Structure of the Glass Industry

The current status of the German glass industry is shaped by three interrelated structural characteristics: strong subsector heterogeneity, continuous high-temperature production, and long-lived core assets. The distinction between hollow glass, flat glass, and technical and other glass matters because technical constraints, product requirements, and likely decarbonisation routes differ substantially. These differences are not secondary. They affect furnace design, energy carriers, production volumes, process control, recycling options, and infrastructure needs. For this reason, any realistic transformation assessment must clearly distinguish between the main glass subsectors rather than assuming a single, uniform transition logic across the industry.^{2,4}

The current industry structure is also closely linked to Germany's position in European and international markets. The glass industry is deeply integrated into cross-border value chains and remains strongly exposed to international competition. This matters for interpreting the current status because plant-level transformation cannot be assessed independently of trade exposure, cost pressure, and location-based competitiveness. The current market environment therefore forms part of the sector's technical baseline rather than merely an external background condition.¹

From an operational perspective, the sector's current state is defined by continuous production and limited tolerance for interruption. Glass production processes must maintain thermal equilibrium and stable melting conditions to preserve product quality. Changes in operating conditions can lead to reject production, and stabilizing the process may take considerable time. This strongly shapes the interpretation of the current status: the installed furnace base must be understood not only as technical equipment, but as a system whose operation is highly path-dependent and difficult to alter in the short term.^{2,5}

8.1.2 Online Data Collection

To capture the current status in a structured way, the roadmap uses a dedicated online tool for site-level data collection. This tool was designed specifically for the roadmap and allowed participating companies to provide information on production sites, products, furnace types, energy use, emissions, plant age, remaining furnace lifetime, and infrastructure conditions. It also provided a basis for collecting information on already implemented measures, ongoing projects, and possible future transformation plans.

The online tool was not merely to compile descriptive company information, but to create a consistent empirical basis for the subsequent scenario analysis. This is important because publicly available information on glass production sites is often incomplete, not directly comparable, or insufficiently detailed to support plant-sensitive modelling. By collecting data directly from the sector, the roadmap aimed to improve the realism of assumptions regarding furnace stock, energy demand, emissions, reinvestment timing, and infrastructure dependency.

A process-based understanding of glass production further informed the assessment, so that site data were interpreted not only in terms of installed capacity and energy use, but also in light of the specific technical requirements of melting and downstream process steps. Plausibility checks complemented the data collection, with follow-up clarifications where necessary and additional industry information where direct site data were incomplete. The results therefore combine primary project data with broader sector evidence. This mixed approach aligns with the roadmap's methodological logic: plant-level transformation pathways must be grounded in actual production conditions rather than inferred only from generic sector averages.

8.1.3 Summary of Site Data

The site-level evidence confirms that the German glass industry's current technological base remains dominated by conventional furnace concepts and fossil energy inputs, especially natural gas. At the same time, electricity already plays an important role in selected applications, including electric boosting, and this role is expected to grow substantially under all relevant decarbonisation pathways. Existing German sector guidance likewise describes the industry as still strongly dependent on gaseous fuels, with electricity already relevant but not yet dominant in the melting process.⁴

The current emissions profile is similarly dual. A substantial share of emissions is still energy-related and therefore linked to fossil fuel combustion in melting

and associated thermal processes. However, process-related emissions from carbonate-based raw materials remain an essential part of the sector's emissions structure. Existing sector strategies consistently underline that these process emissions are structurally more difficult to eliminate than combustion emissions and must therefore be considered separately when assessing both the current status and future transformation options.^{2,4}

The site data also confirm the importance of infrastructure constraints. The current status of a glass site depends not only on furnace type and fuel mix; it also depends on grid access, site connection capacity, possible electricity upgrades, and future hydrogen availability. This is one reason the same decarbonisation technology cannot be assumed to be equally available across all sites. Electricity connection upgrades, infrastructure lead times, and supply security are repeatedly identified as critical conditions for advanced decarbonisation strategies.^{2,16}

Another important current-status finding concerns reinvestment windows. Because furnace lifetimes are long and rebuild cycles infrequent, the age structure and expected remaining lifetime of existing assets are highly relevant to transformation planning. Sector strategies typically refer to furnace lives of roughly one to two decades, and hybrid concepts are often justified because they allow plants to preserve technological optionality under uncertain infrastructure conditions. In the context of this roadmap, the current installed furnace stock is therefore not just an engineering baseline; it is also a timing constraint on the transformation itself.²

The broader economic context further sharpens the interpretation of current site data. The sector is not operating in a comfortable transition-readiness environment, but under continued market pressure, high energy-cost exposure, and intense international competition. According to BV Glas, turnover from January to November 2024 fell by 10.7%, while total production in the first three quarters of 2024 declined by 7.8% year on year. This matters because

the sector's technical status cannot be separated from its financial and competitive position.¹⁴

8.1.4 Overview of Ongoing Research and Development Projects

The sector's current status is not defined solely by the existing installed base; the growing portfolio of ongoing research, development, and demonstration projects also shapes it. These activities matter because many key decarbonisation technologies are not yet mature or proven across all segments and production scales. They therefore shape the sector's empirical present, not just its hypothetical future.

A first major field of activity concerns electrified and hybrid furnace technologies. European industry reports show that glassmakers are increasingly moving beyond conceptual discussion and into industrial experimentation with electric, hybrid, and super-hybrid melting concepts. The European Container Glass Federation (FEVE) documents a growing number of projects in which hybrid furnaces combine high shares of renewable electricity with low-carbon combustion inputs, illustrating that such concepts are already being tested under real production conditions.^{2,50}

A second field concerns hydrogen-related process development. Hydrogen remains technically promising but is constrained by infrastructure and cost. At the same time, project activity has intensified markedly. British Glass refers to ongoing work on hydrogen combustion and hydrogen blending in glass melting, while German sector documents also point to dedicated R&D efforts on hydrogen use in glass furnaces. These developments show that hydrogen is no longer merely a speculative option, but is increasingly being tested in practical industrial settings.^{2,4}

A third field concerns flat-glass-specific decarbonisation projects. In this segment, technical constraints are especially demanding because of large

furnace sizes and strict product-quality requirements. This makes current pilot projects particularly relevant. One prominent example is the Volta line inaugurated by AGC and Saint-Gobain on 12 February 2025 in Dubí, Czech Republic. According to the companies, this project is based on a world-first pilot furnace concept and is intended to support lower-carbon flat glass production under real industrial conditions.^{8,13}

The German context also makes clear that ongoing project activity must be interpreted together with infrastructure and policy conditions. Demonstration projects are not isolated technical pilots; they are embedded in a broader transition environment in which industrial learning, infrastructure rollout, electricity-market conditions, and policy support need to interact if decarbonisation is to move from pilot scale to wider deployment.⁵¹

8.1.5 Patent Analysis

The patent analysis complemented the literature review, site-level data collection, and stakeholder input by providing a forward-looking perspective on technological innovation trends relevant to decarbonising the glass industry. Its purpose was not to infer commercial deployment directly, but to identify broader directions of technological development, innovation dynamics, and the emergence of new or improved melting concepts, components, and process solutions.

The patent search was designed as an international review of patent activity from 2000 to 2025, with a particular focus on innovations in glass-melting technologies and associated decarbonisation measures. The search strategy combined keyword searches with relevant IPC classes, where appropriate. General search terms covered glass production and melting technology, including melting furnace, glass-melting plant, glass production, melting process, and melting technology. More specific terms captured particular furnace concepts and technological approaches, including U-flame furnace, oxy-fuel melting furnace, electric melting furnace, float glass melting furnace, hybrid melting furnace, and

regenerative melting furnace. The search also included terms linked to technical components and process-related innovation, such as molybdenum electrodes, exhaust gas cleaning, flue gas/combustion air reversal systems, horizontal stirrers, energy efficiency, glass recycling and cullet utilisation, CO₂ reduction technologies, and simulation and optimisation of melting processes.

The analysis drew on specialized patent databases for both national and international coverage. We reviewed German patents using DEPATISnet and DPMAregister, and used Google Patents to expand the search to international patent activity. We screened the retrieved patent records and grouped them into broad thematic categories, including furnace design, electric and hybrid melting systems, hydrogen- and oxygen-related combustion technologies, exhaust gas treatment, process optimization, energy-efficiency measures, recycling-related innovations, and CO₂ reduction solutions.

The results indicate that innovation activity is currently highly concentrated in a limited number of search categories. Based on the raw patent result set, 70.3% of retrieved records were associated with electric melting furnace searches, followed by hybrid melting furnace searches (16.3%) and float glass melting furnace searches (10.7%). Together, all remaining search categories accounted for only 2.7% of the raw results. This suggests that current patenting dynamics are strongly concentrated in electrification-related and hybrid furnace concepts. In contrast, more conventional combustion-based furnace types play only a comparatively minor role in the overall patent landscape. At the same time, the manual screening showed that, especially in the electrification-related search fields, substantial activity also comes from adjacent technology areas beyond glass manufacturing itself, including batteries, electronics, materials processing, and powder metallurgy. These proportions should therefore not be interpreted as direct indicators of sector-specific deployment, but rather as signals of broader technological momentum and innovation direction.

The patent analysis informed the roadmap in three ways. First, it helped to identify which technological fields currently show sustained innovation activity. Second, it indicated which decarbonisation options are being pursued internationally beyond the projects and actors directly covered by the empirical survey and interview work. Third, it supported a broader assessment of technology maturity and future relevance, especially when interpreted alongside current demonstration projects and stakeholder perspectives. At the same time, the method has important limitations: patent activity does not automatically imply industrial relevance, commercial readiness, or large-scale applicability. This is especially true in broad search fields, where patent counts are inflated by overlap with adjacent sectors and generic process technologies. For this reason, the patent analysis should not be interpreted in isolation, but as one analytical building block alongside the roadmap's broader empirical and literature-based evidence base.



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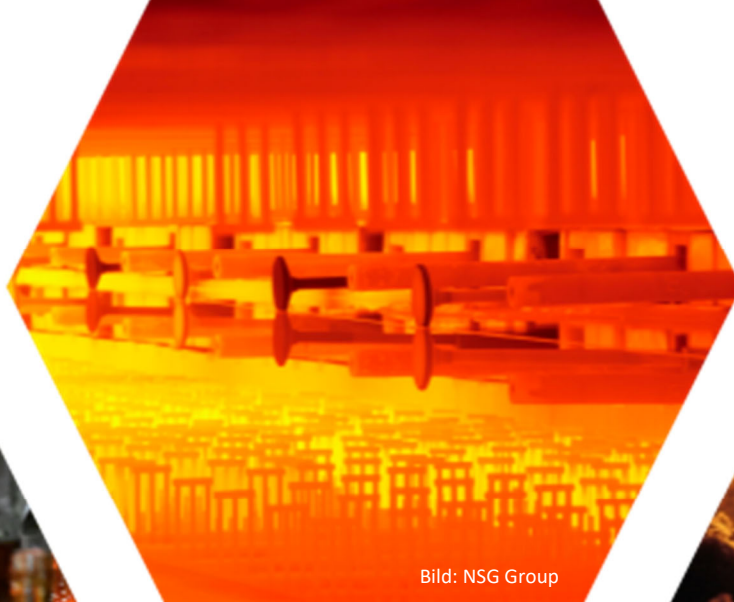


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