Energy Flexibility in the German Glass Industry

Final Report

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Preface

A successful decarbonization of the glass industry requires reliable framework conditions under consideration of technological limitations.

The German glass industry faces the key challenge of making its production climate-neutral by 2045. Companies are continuously investing in new technologies, exploring alternative energy sources, and working to avoid CO_2 emissions as much as possible.

At the same time, we must recognize that the options for action are limited by the physical and process-related conditions of glass production. The central melting process is continuous, high-temperature dependent, and extremely sensitive to fluctuations. Technical limitations mean that short-term load shifts or flexible electricity use are generally not possible without compromising product quality or the service life of the equipment.

This study on *Energy Flexibility in the German Glass Industry* makes it clear that the industry is striving for decarbonization—but to achieve this, it needs reliable political framework conditions that recognize its technological realities. Blanket requirements for industrial flexibility or the complete elimination of existing grid fee privileges could be counterproductive because they make more environmentally friendly options such as electrification uneconomical.

We hope that this study will contribute to a more nuanced understanding—and to ensuring that the transformation of the glass industry remains feasible and future-proof.

Christiane Nelles
Managing Director, BV Glas

September 2025

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Executive Summary

The reason for the study is the planned expiry of the so-called 'band load regulation' on 1 January 2026, which represents a reduction in grid fees for electricity-intensive end consumers. A transition period until 31 December 2028 applies to end consumers. The 'band load regulation' encourages end consumers to consume electricity as consistently as possible. With an annual electricity consumption of over 10 GWh and at the same time over 7,000 full-load hours (FLH), a discount of up to 80 % on grid fees is applied. A planned revision of grid fee privileges, among other things to integrate fluctuating renewable electricity generation into the energy system, is intended to activate energy flexibility potential and incentivize flexible, grid-friendly electricity consumption.

To answer the question of whether and to what extent the glass industry can provide such energy flexibility potential, this study examines the processes of glass production in the status quo and provides an outlook on future developments, taking into account possible transformation paths. To this end, interviews and on-site visits with container glass manufacturers and glass producers are being conducted.

Glass production is characterized by continuous, energy-intensive and temperature-sensitive processes. The thermal equilibrium of the glass melts is essential for product quality. Adjustments to the process parameters usually lead to production rejects, which severely limits the energy flexibility potential. The foreseeable decarbonization of the industry will primarily take place through electrification using all electric or hybrid melting furnaces. These significantly increase electricity demand without creating any new relevant flexibility potential. Hybrid furnaces theoretically offer scope for varying the electricity-gas ratio, but these adjustments are technically complex, time-consuming and only feasible in the long term, as well as associated with risks to efficiency and service life. Energy storage systems such as battery systems could enable flexibility outside the core process, but they are challenging in terms of economics and infrastructure.

Regulatory incentives to activate an energy flexibility potential can only be effective if they take into account the technical limitations of glass production. Continuous, efficient, high-quality and economically viable production remains the top priority. The individual location- and product-specific requirements of manufacturers must be taken into account in the design of network fee systems.

Key Findings of the Study

1

Diversity in glass manufacturing
Each location and each product in the glass industry has its own highly individual requirements and conditions for achieving the desired product quality. It is particularly important to distinguish between the individual sub-sectors of flat glass, hollow/container glass and speciality glass.

2

Technical reasons: Low energy flexibility potential in the manufacturing process
All glass production processes must run continuously in order to maintain the set thermal equilibrium in the process and thus the desired product quality. Changes to the process have a direct impact on product quality and usually lead to production rejects. Due to the thermal inertia in the process and the sometimes long dwell times in the melt, it takes several days to weeks to adjust operating points and obtain a usable product that meets quality requirements.

3

Decarbonization: Rising electricity consumption, consistently low energy flexibility potential
The decarbonization of the glass industry is based primarily on increased electrification, either through all electric or hybrid melting furnaces. Both technologies significantly increase the electricity consumption of production sites. However, the processes must continue to be operated continuously and without significant energy flexibility potential in order to maintain product quality. The elimination of band load privileges makes electricity procurement considerably more expensive and, especially in the case of hybrid melting tanks, means that the use of fossil natural gas is the more economical option. The goal of decarbonization should be prioritized and supported by appropriate incentives, including in the grid fee system.

4

Flexibility vs. efficiency, service life and economic utilization
Adjustments to the operating points of the melting tank usually take hours to days, and in some cases weeks. Each adjustment is associated with product waste and reduces the lifetime of the melting tanks and, in some cases, the transformers. In order to operate a melting tank economically, it must be continuously utilized under full load for as long as possible. Any adjustment of the operating point also reduces the energy efficiency of the melting tank. Hybrid melting tanks in particular are designed for maximum efficiency, both in terms of their tank size for the planned number of electrodes and in terms of the size of the top furnace for the associated gas flame, in accordance with an optimum operating point.

5

Costs and economic risks in electricity procurement
The costs incurred by the elimination of baseload privileges cannot be offset by alternative revenue opportunities, such as conceivable marketing on the control energy market. The technically feasible energy flexibility potential for providing the corresponding power is too low for this. In addition, baseload supply is often secured several years in advance through long-term electricity purchases, depending on the risk appetite of glass producers, in order to hedge against price risks, with only a small portion being procured at short notice via the spot market. In order to be able to react to price signals, electricity procurement would have to be more strongly oriented towards the spot market, which would lead to a greater risk of dependence on short-term price fluctuations. Since the processes must be operated continuously and do not offer any relevant energy flexibility potential, electricity would then also have to be purchased even if prices were high in the short term.

1 Motivation for the Study and Regulatory Framework

Due to the increasingly fluctuating generation of renewable energies, energy flexibility in the electricity system is becoming increasingly important Therefore, regulatory incentives are intended to unlock industrial energy flexibility potential, but they must also take into account process-specific technical conditions.

As an energy-intensive industry, the glass industry currently benefits from grid fee privileges that encourage consistent electricity consumption. However, glass production is based on a continuous production process with no obvious potential for energy flexibility. In order to take the technical requirements of the glass industry into account when revising the network fee privileges, this short study provides an objective and technically well sound assessment of the current and future energy flexibility potential in the glass industry. The study considers the various similarities and differences between individual locations and product branches, such as flat glass hollow/container glass, and speciality glass.

1.1 Objective and Methodology of the Study

The study aims to provide a comprehensive assessment of the current energy flexibility potential in the status quo, as well as an outlook for the target year of German climate neutrality in 2045. This will take into account the corresponding transformation options.

Initially, statistical sources, industry and association assessments [1], and scientific studies such as [2], [3], and [4] are used.

Secondly, practical experience and expertise are incorporated. In order to do so, five different **glass producing companies** from the flat glass, container glass, and specialty glass sectors are interviewed as part of the study, and some of the processes will be inspected on site.

The **glass melting tank** is the core component of glass production and the most energy-relevant process step. For this reason, the three relevant German glass tank manufacturers were also interviewed.

This **final report** first provides an overview of the regulatory framework with regard to energy flexibility, the status quo of energy consumption, and the currently possible load flexibilities in the glass industry. The findings from the practical interviews form the main part of the analysis. Finally, there is an outlook for the year 2045 and the impact of possible transformation pathways on energy flexibility potentials.

1.2 Regulatory Framework

Currently, electricity customers pay grid fees as the charge for using the electricity grids and for the provision of a contractually agreed connection capacity by the grid operators. These fees are initially independent of distance and, for industry, generally consist of a working price (cents per kWh) and a capacity price (cents per maximum kW consumed).

Exceptions are regulated by **special grid fees**, which can be granted either to take account of special circumstances or to encourage certain consumer behaviour. The Electricity Grid Fee Ordinance (Stromnetzentgeltverordnung, StromNEV) [12] currently contains two such special grid fees for industry and commerce (§ 19 (2) StromNEV), which create opposing incentives for grid usage: The so-called **band load** and **atypicality.** In 2024, these special grid fees resulted in savings of over €1 billion for all affected companies in Germany [13]. This relief is passed on as additional costs to other grid users.

Band load (electricity-intensive grid usage)
Electricity-intensive end consumers with a constant electricity consumption receive a reduction in grid fees. This regulation applies to annual electricity consumption of over 10 GWh and, at the same time, over 7,000 full-load hours (FLH). Full-load hours are calculated by dividing annual electricity consumption by peak load.

A discount of up to 80 % on grid fees is applied at a minimum of 7,00 FLH. This regulation is therefore often referred to as the "7,000 h regulation". Further discounts apply at 7,500 FLH(up to an 85 % discount) and 8,000 FLH (up to a 90 % discount). The aim of this regulation is to encourage a constant base load consumption among electricity-intensive end consumers and thus ensure grid stability in the current energy system.

Continuous consumption reduces the feed-in from base load power plants, providing the operators with planning security for expected consumption.

Atypicality (atypical grid usage)
Atypicality creates an incentive for energy flexibility. The aim is to limit the necessary grid dimensioning and, consequently, grid costs. The simultaneous annual peak load of all connected consumers is decisive for grid design. The atypicality regulation therefore includes grid fee reductions for end consumers, if they shift their individual annual peak load significantly outside one or more typical time windows per season, during which the simultaneous annual peak load of all withdrawals from the grid occurs . These peak load time windows must be determined separately by each grid operator and each grid or transformation level. This can reduce grid fees for end consumers by up to 80 %.

1.3 Key Issues Paper from the Federal Grid Agency

On July 24, 2024, Decision Chamber 4 of the Federal Grid Agency (Bundesnetzagentur, BNetzA) published the "Key points paper on the further development of industrial grid fees in the electricity sector" [13]. This paper outlines the reasons for, key background information on, and objectives of a new regulation of special grid fees. These are summarized below.

The BNetzA originally intended, among other things, to phase out the band load regulation on January 1, 2026. At the same time, the general network fee system (Allgemeine Netzentgeltsystematik, AgNes) is also being reviewed. The aim is to create a long-term effective regulation that meets the requirements of the energy transition and provides companies with a permanent, reliable basis for planning the investments required to convert their production processes. The necessary adjustments for consumers are to be made possible within sufficient regional and industry-specific transition periods. As described below, contrary to the original announcements, the revision of the special grid fees will be integrated into the AgNes process.

The reason for the new regulations is **the change in requirements in the energy system,** particularly in electricity generation, as a result of the energy transition. Increasingly fluctuating electricity generation from renewable energies is leading to rising costs for grid expansion, balancing energy, and congestion management. These systemic overall costs can be reduced by dynamic responses from consumers (especially electricity-intensive industrial companies) on to the prevailing feed-in situation.

In particular, the **band load** criteria currently prevent energy-intensive end consumers from becoming more flexible, as flexible electricity procurement jeopardizes the achievement of the "7,000 h limit." Abolishing the band load criterion would, in return, enable flexible consumers to generate additional income, for example by participating in the balancing energy market.

Atypicality is also no longer an effective tool for relieving the grid in networks with a high proportion of renewable energy feed-in, as generation is shifting away from base load power plants toward PV and wind energy with daily to seasonal fluctuations and generation peaks, and electricity demand should increasingly be geared toward generation.

The planned new regulation is intended to create targeted incentives to achieve positive effects for the integration of renewable energies and system-friendly behavior on the part of users.

This also requires the implementation of European and national **legal requirements** for the design of grid fees. In particular, two principles must be taken into account when designing a new special grid fee regulation:

- **Cost orientation:**
  Grid fees should both reflect the costs of grid operation and contribute to the overall efficiency of the grid through price signals.
  (Art. 18(1) subparagraph 2 sentence 1 of Regulation (EU) 2019/943)
- **Promotion of energy efficiency:**
  Grid fees must lead to the efficient and sustainable use of available energy. In particular, curtailment of renewable energies should be avoided and market integration of renewable electricity should be encouraged.
  (Art. 18(2) sentence 1 of Regulation
  (EU) 2019/943,
  Art. 27(7) of Directive (EU) 2023/1791,
  § 21(2) sentence 6 of the Energy Industry Act
  (EnWG), Art. 194(1)(c) of the Treaty on the Functioning of the European Union (TFEU))

However, the final design and implementation of new incentive mechanisms also depends on the technical capabilities of end consumers in industry to forecast volume and price developments and then respond flexibly to them. The market signal for this is to be strengthened. At the same time, the actual and future energy flexibility potential of individual consumers is to be taken into account and realized.

It is particularly relevant here that flexibility efforts are significantly more challenging for production-related band load consumption than for other usage patterns.

In order to take consumer circumstances into account in practice, the BNetzA is calling for comments on the redesign of special network charges. Key questions have been provided for this purpose. The questions focus on current production processes and developments over the next five to ten years. They are divided into three subject areas:

Quantity potentials

- How long will the ramp-up and ramp-down periods take?
- What is the volume of the residual load that can be used flexibly?
- Can the share of residual load in the various industrial sectors be increased and, if so, to what extent?

Predictability of price fluctuations

- To what extent are various industrial sectors already responding to electricity exchange prices in terms of residual loads?
- What methods are used to forecast price developments and how reliable are they?
- How is the potential assessed for increasing the reliability of forecasts in the coming years?
- What level of granularity can be achieved in terms of flexibility? Can a response be implemented on a quarter-hourly basis (intraday prices)?

Flexibility processes

- What measures are necessary to achieve maximum flexibility in processes?
- What costs are associated with such measures?
- How long will these measures take?

Course of the discussion

The interim report of this study, published in September 2024, formed an initial scientific basis for the requested statement.

In July 2025, the Federal Grid Agency (BNetzA) suspended the transfer of the determination procedure for industrial grid fees to the separate Decision Chamber 4. Instead, the issue is to be integrated into the framework determination for the general electricity grid fee system (AgNes). To this end, a separate hearing on industrial grid fees is planned within the procedure. The draft determination is planned for the end of 2026.

2 Fundamentals of Industrial Energy Flexibility

Load flexibility is divided into load reduction, load increase, and load shifting. Various energy flexibility measures are available to industrial companies for this purpose. The intersection of economic and practically usable energy flexibility potential results in the actual realizable potential, which can then be tapped into.

According to the Association of German Engineers (Verein Deutscher Ingenieure, VDI) definition, **energy flexibility** is "the ability of a production system to adapt quickly and efficiently to changes in the energy market. Product quality must remain unchanged." [5]

The resulting load change is considered to be a change in the power consumed compared to reference operation [6]. Three options for load flexibility can be identified (see Figure 2-1), which are also referred to as Demand Side Management (DSM) :

- **Load reduction:** Reducing the power consumed, e.g., by temporarily shutting down machines.
- **Load increase:** Increasing the power consumed**,** e.g., by increasing the production volume (with temporary storage if necessary) and
- **Load shifting:** Adjusting production times so that load increase and reduction are carried out directly after each other and the effects of both sub-measures thus compensate each other without resulting in a total loss of production.

Examples of flexibility measures include changing energy sources (hybridization), energy or product (interim) storage, changing the production sequence, or interrupting processes.

In order for energy flexibility potential to be tapped into and made available to the market, the associated energy flexibility measure must be technically feasible, practicable in practice, and economically viable from a business perspective. [7]

As already described in the previous chapter, flexible adjustment of electricity demand will become increasingly necessary in the future in order to avoid grid instabilities. The increased fluctuation in renewable energy generation can lead to imbalances in the power grid. Flexible electricity consumption that is adapted to generation helps to maintain the balance between generation and consumption. This ensures the stability of the power grid. Other positive effects of industrial energy flexibility can include:

- **Cost optimization** from the end consumer's perspective by purchasing electricity at times when prices are lower
- **Increased security of supply** through flexible adjustments to grid fluctuations to prevent overloads, and
- **integration of renewable energies** into the energy system by purchasing electricity at times when there is a large amount of renewable generation available.

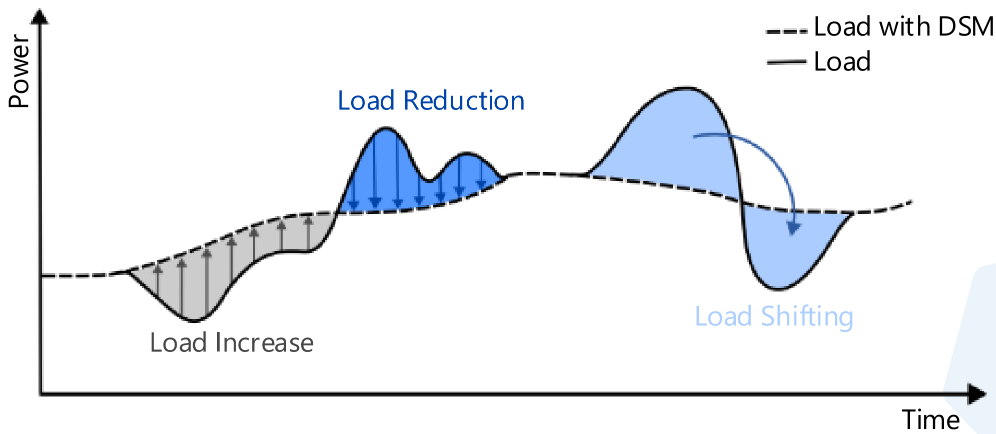

Figure 2-1: Schematic representation of energy flexibility options (own illustration, FfE).

3 Status quo of the Glass Industry

The energy-intensive glass industry is divided into the production of flat glass, hollow/container glass, and specialty glass. While the specific production processes vary from site to site, the melting process is the most energy-intensive step in all of them.

The glass industry comprises around 400 companies in Germany and is one of the country's most important industrial sectors. With around 54,000 employees, it is one of the largest sectors in the industry. In 2024, the German glass industry achieved a turnover of approximately €11.3 billion (2023: €12.3 billion €) [14].

The glass sector is characterized by a wide range of products and numerous fields of application, which result in a heterogeneous structure. The product portfolio includes container glass for food and cosmetics, flat glass for the building sector, and special and utility glass. The subdivision of the glass industry, for example based on production indices (Figure 3-1), shows that the various sub-sectors develop independently of one another and must be considered separately.

Approximately 6.7 million tons of glass are produced in Germany each year, with the largest share accounted for by the container glass industry (approx. 3.8 million tons per year), followed by the flat glass industry (approx. 1.8 million tons per year).

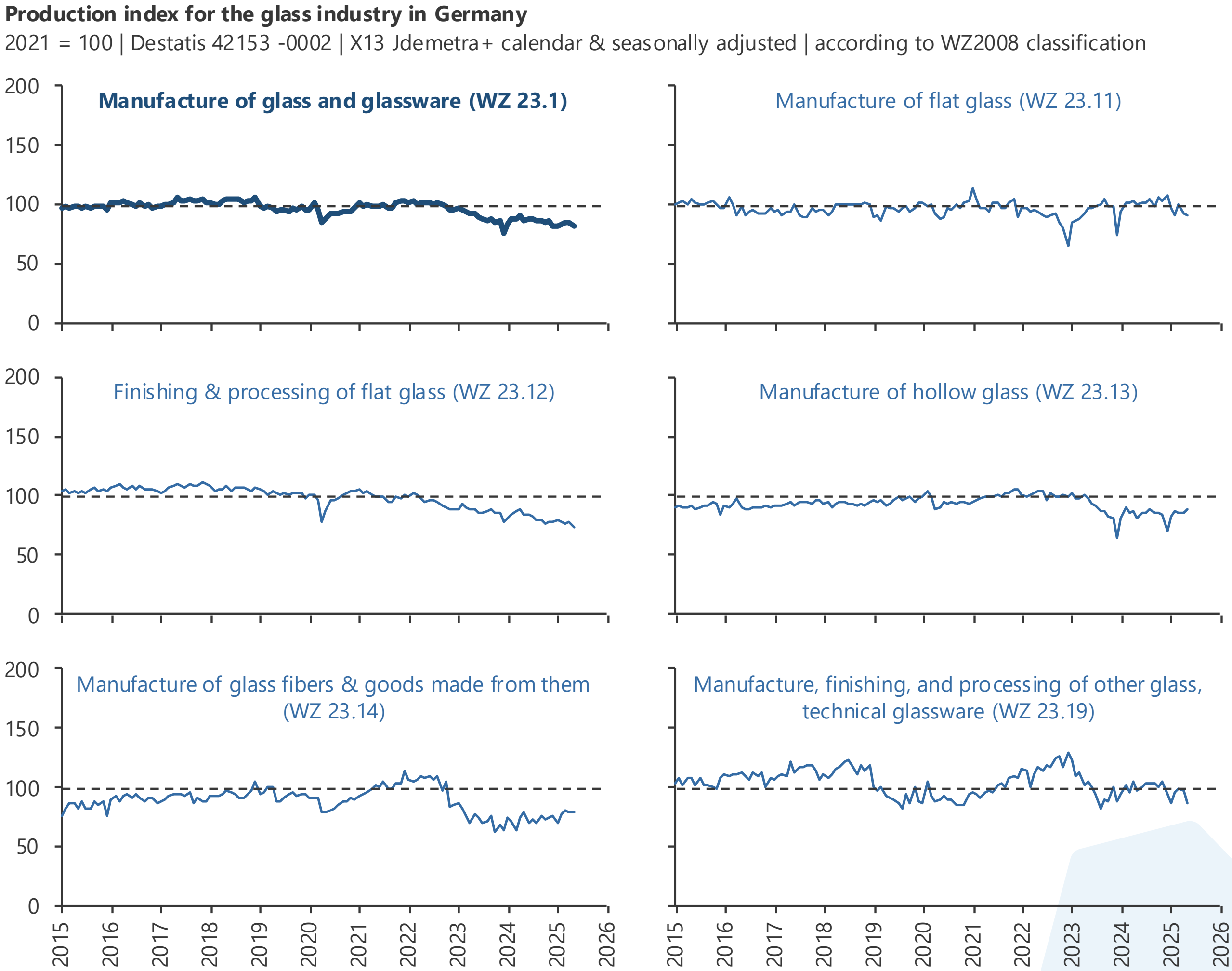

Figure 3-1: Production index of the glass industry and related sub-sectors over the past ten years.

Although the specialty and utility glass sector accounts for only a small proportion of total production in terms of volume, at around 0.3 million tons per year, it is another key sub-sector of the glass industry due to the relevance of the products manufactured and the high added value. [14]

Due to the heterogeneous product groups, very different production technologies are used in these three key sub-sectors, which further exacerbates the challenge of decarbonization. In order to develop a decarbonization strategy for the German glass industry, the sub-sectors of container glass, flat glass, and specialty and utility glass were therefore examined and analyzed separately. [1] [15]

The Manufacturing Process

The basic steps of glass production (see Figure 3-2) are the same in all sub-sectors. First, a mixture of raw materials (including quartz sand, soda, lime) and cullet is prepared. This is then melted in a melting furnace in the most energy-intensive step of glass production. Here, the raw materials are liquefied into glass and then purified to remove impurities and produce a uniform glass mass. Depending on the type of glass produced, this process accounts for around 60 to 80 % of the total energy required in glass production, which is currently still almost exclusively covered by fossil fuels. Measures aimed at tapping into relevant energy flexibility must therefore focus primarily on the melting process.

The melting process is followed by further production steps, which are referred to as downstream processes. These include, for example, shaping the glass, tempering (a heat treatment to increase strength), or cutting and finishing the end product. Although fossil fuels are still used in these steps, the energy requirements are significantly lower than in the melting process, and electrification of these areas can be implemented without major technological hurdles.

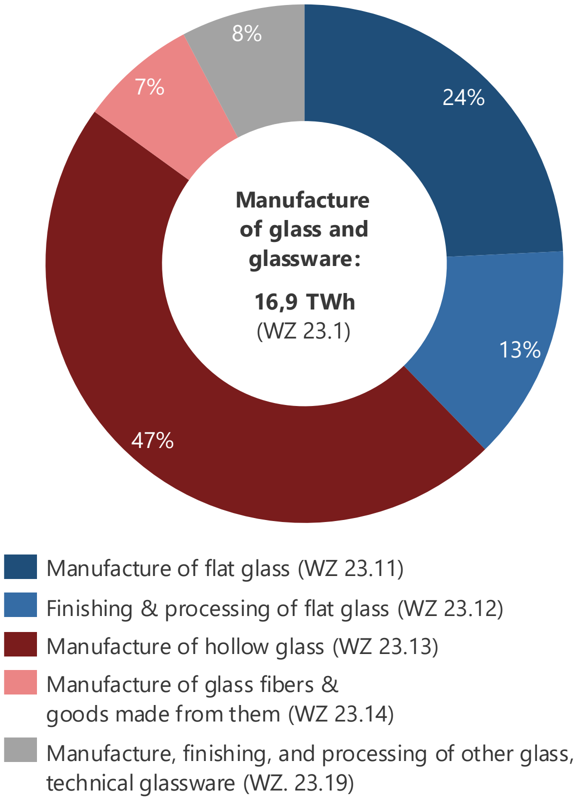

Figure 3-3: Final energy consumption of the sub-ranches in the glass industry (2023) [11].

Energy demand

The energy requirements of the glass industry (WZ 23.1: Manufacture of glass and glass products) amounted to 16.9 terawatt hours (TWh) in 2023, accounting for approximately 3 % of the total energy requirements of the industrial sector [16]. Natural gas remains the most important energy source in glass production, followed by electricity (see Table 3-1) [11].

The majority of the energy, up to 85 %, is required for the heat supply. The high process temperatures required for glass production are the reason for the very high energy demand. Almost 90 % of the processes require temperatures above 500 °C, with the temperature in the melting furnaces, which form the heart of glass production, ranging between 1,400 and 1,650 °C.

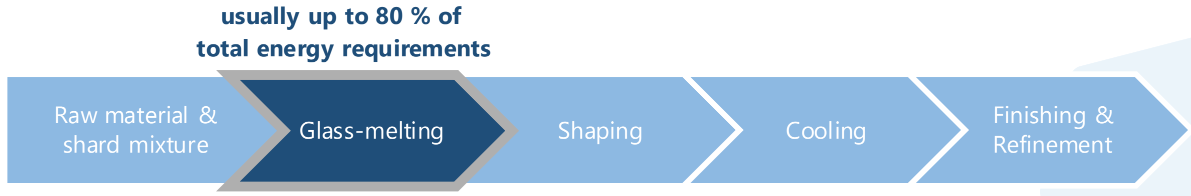

Figure 3-2: Simplified process diagram of glass production.

The specific energy requirements for glass production vary greatly and depend largely on the length of time the glass spends in the production process, especially in the furnace. Depending on the length of time, energy requirements can increase up to fourfold. This illustrates the complexity and challenges associated with efficient energy use in the glass industry.

The production of hollow glass accounts for the largest share of energy consumption (47 %), followed by the production of flat glass (24 %) (see Figure 3-3).

To increase efficiency, state-of-the-art heat recovery measures are used in all glass furnaces. This is possible, for example, via steam turbines up to a temperature of 400 °C or through regenerative preheating of the combustion air. Nevertheless, natural gas is currently the dominant energy source, especially for large melting furnaces. All electric furnaces, which are becoming increasingly important as an alternative technology, are currently used more for smaller production volumes or smaller furnace sizes, as they are currently less efficient on a large scale and have limited melting capacity. Hybrid furnaces are powered by both natural gas and electricity.

Electrification – status quo

All electric melting furnaces are already used in the glass industry, especially for smaller production capacities (up to 50 tons per day) for cosmetic and specialty glass. In the container and flat glass industry, a process known as "boosting" is used, in which 5 to 15% of the melting energy is additionally supplied electrically via electrodes in order to increase production capacity and improve glass quality. Due to the higher cost of electricity compared to natural gas, electric melting has so far only been used for special types of glass. All electric furnaces have limited melting capacity. Large melting furnaces for container and flat glass cannot therefore be heated purely by electricity . [3] [1] [15]

Table 3-1: Energy carrier use in the German glass industry in 2023. [11]

Energy carrier	Absolute energy consumption	Relative share	...of which for heat generation
Natural gas	12.2 TWh	72 %	50 - 85 %
Mineral oil products	0.8 TWh	5 %	
Electricity	3.8 TWh	22 %	
Other	0.1 TWh	1 %	
Total	**16.9 TWh**	**100 %**	**50 – 85 %**

4 Transformation Pathways for the Glass Industry

The transformation of the glass industry is possible through the electrification of melting furnaces, the use of green hydrogen, or a hybrid use of both energy sources. All transformation paths lead to higher electricity consumption by glass producers.

The BV-Glas roadmap "Glass 2045 – Decarbonization of the Glass Industry" (original: „Glas 2045 – Dekarbonisierung der Glasindustrie“) [1], published in 2022, shows three greenhouse gas reduction paths in addition to a reference path (business as usual):

- an electrification scenario,
- a hydrogen scenario, and
- a hybrid scenario.

In the reference path, the share of furnace technologies in total glass production remains unchanged, while in the electrification scenario there is a shift to predominantly all electric furnaces and in the hydrogen scenario to hybrid H_2-furnaces (Figure 4-1).

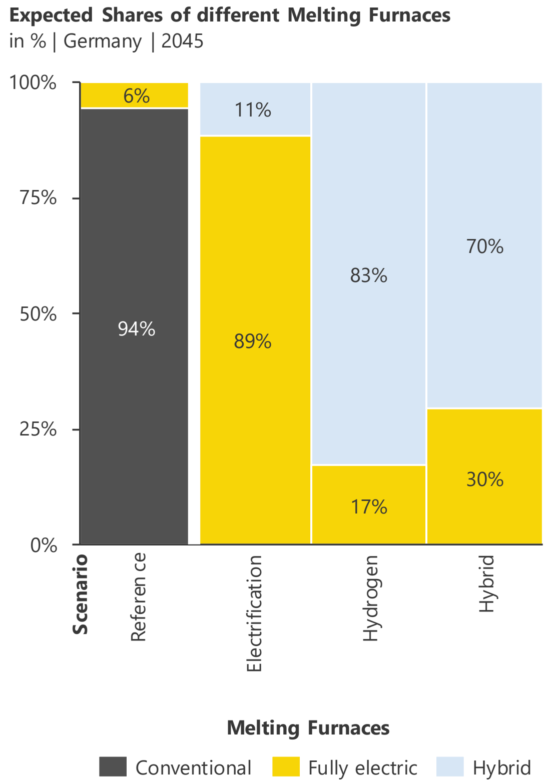

Figure 4-1: Share of melting furnaces in the transformation paths of the BV Glass Roadmap [1].

For the target year 2045, energy consumption in the reference scenario is 14.0 TWh/a, of which approximately 1.9 TWh/a is attributable to electricity. The three transformation paths considered (see Table 4-1) all achieve lower total energy consumption, ranging from 9.5 TWh/a in the electrification scenario to 12.2 TWh/a in the hydrogen scenario. However, electricity consumption rises sharply in all transformation paths. In the hydrogen scenario, it amounts to 4.3 TWh/a, and in the electrification scenario, it is as high as 8.7 TWh/a.

Table 4-1: Annual energy and electricity consumption in 2045 in the scenarios of the BV Glass Roadmap [1].

Scenario	Energy consumption	... of which electricity
Reference	14.0 TWh/a	1.9 TWh/a
Electrification	9.5 TWh/a	8.7 TWh/a
Wasserstoff	12.2 TWh/a	4.3 TWh/a
Hybrid	10.7 TWh/a	8.3 TWh/a

It is clear that electricity consumption in the glass industry will increase significantly in all of the transformation paths considered. Ensuring the availability of renewable energy sources, especially electricity, is therefore one of the recommendations for action in the roadmap. To achieve this, the energy infrastructure must be expanded and electricity must be available economically and continuously. The consideration of energy flexibility options or new energy flexibility potentials through transformation is not part of the roadmap and should therefore also be considered below from the perspective of the transformation pathways presented.

Further research activities relating to energy flexibility in the glass industry

As part of the Kopernikus SynErgie project, which is investigating the flexibilization of energy-intensive industries [2], there is also a satellite project in the glass industry. As part of the DisConMelter research project, an electric glass manufacturing process of the same name was developed that makes it possible to produce container glass whenever there is a surplus of electricity in the grid. The DisConMelter is an electrically powered melting tank designed to make glass production more flexible. The system consists of three modules: In the first module, glass is melted when there is surplus electricity in the grid. The molten glass is fed into module 2, a glass storage tank that can store the liquid glass with low energy loss. The storage facility is energy-flexible, meaning it can be operated with changing loads . Finally, module 3 takes over the further processing of the glass into end products. The modular design has two advantages: more flexible energy use for grid stabilization and the possibility of reducing night and weekend shifts through temporary production interruptions. The process was set up and operated on a small scale in a test module at the Deggendorf Institute of Technology. The project was completed in 2019. No further developments towards market maturity are known.

In the FlexMelter [17] from *Nikolaus SORG GmbH*, a ceramic wall between the batch and the melt is also intended to separate the processes. However, in practice, the furnace design proved to have a very short service life, and stones detaching from the partition wall in the product compromised the required quality. Therefore, no return of the FlexMelter is currently foreseeable.

5 Key Findings from the Interviews

Glass production is a diverse, complex process with individual, site-specific requirements. After changing process parameters, it often takes several hours to days for a new thermal equilibrium to be established. It then takes another few hours to days before the product can be manufactured to the required quality. Energy flexibility options are therefore very limited in terms of process technology and cannot currently be exploited on a relevant scale.

The expertise and perspectives of practitioners were gathered in online interviews and on-site process inspections. These included **glass furnace manufacturers** as well as **flat, specialty, and container glass producers.** The initial focus was on the status quo of the glass industry and possible energy flexibility potentials that have not yet been tapped. Possible development paths were also considered in order to provide an outlook on future technologies.

5.1 Perspective of Glass Furnace Manufacturers

The glass melting furnace manufacturers interviewed are all companies with over 100 years of tradition and experience, offering a broad product portfolio of glass melting furnaces. These furnaces should generally meet three criteria:

- They must be as **durable** as possible and resistant to the high temperatures and aggressive components of the molten glass,
- they must enable glass producers to manufacture glass products with the required high **quality and purity**, and
- they must be as **energy-efficient** as possible to enable economical production.

To this end, modern furnaces are equipped with a variety of monitoring systems that enable precise control of the melting conditions.

5.1.1 Glass Furnaces in the Status quo

In the status quo, five types of furnaces are primarily used for glass production, which are similar in the portfolios of all manufacturers.

Four of these furnace types are fired with **natural gas**. The flame burns above the raw material mixture, which is melted from above. All of these furnaces can be electrically supported by additional electrodes that heat the mixture from below. This process is known as *boosting* and has been used primarily for tonnage adjustments. Depending on the furnace and product type, boosting can achieve an additional energy input of approximately 5 to 25 % (in individual cases up to 40 %). Higher electricity shares require a special hybrid furnace design (see below). For some product types, boosting is not possible.

- The regenerative **end fired furnace** is the most widely used type of furnace in the container glass industry. It is characterized by its very compact design. Natural gas is blown into the furnace at the front end via burner lances, and preheated air is blown in via a burner neck located above the burner lances. The resulting flame is deflected at the other end of the furnace and burns in a U-shape. The exhaust gases are led out of the combustion chamber via the second burner neck. The burners used for firing are used alternately and replaced every 20 to 25 minutes, whereby the flame direction is reversed each time. The hot exhaust gases are used via regenerators to preheat the combustion air. Provided there is sufficient space and the products allow it, these furnaces can be prepared for retrofitting with electrodes during cold repairs (according to the manufacturer, every 15 to 20 years for flat glass production or every 12 to 15 years for container glass production) and then operated with a maximum of 20 % electricity. Partial electrification is limited because as the electrical heat input increases, the required flame temperature decreases until the flame would no longer circulate hot enough across the entire furnace area. Retrofitting electrification increases the temperature and affects the flow convection in the melt, which can lead to increased corrosion of the furnaces.

- The regenerative **cross fired furnaces** are also operated with an air-natural gas mixture. By arranging the burners along the side in the direction of flow, larger heating zones and thus higher melting capacities of around 1,000 to 1,200 tons per day can be achieved. Both types of regenerative burners must be started up and shut down slowly in order to achieve the desired thermal equilibrium in the melt.
- **Recuperative furnaces** are also based on natural gas combustion with air, predominantly with a side burner arrangement, and have lower capacities than regenerative cross-heated melting furnaces. Instead of regenerators, double-jacketed/split or tube bundle recuperators are used for air preheating. These are less efficient than regenerators. However, the flue gas subsequently has a higher temperature than in regenerative furnaces and can therefore be used, for example, for energy recovery by means of a steam turbine. Recuperative burners must be operated continuously and the gas flow can only be changed very slightly, as a significant reduction in burner output would require the burners to be removed, which is a costly process
- In **oxyfuel furnaces,** natural gas is burned with pure oxygen. Preheating is technically limited, as otherwise the oxygen becomes too reactive and the natural gas tends to undergo thermal decomposition (cracking). The burner lances must always be cooled by the oxygen and gas flow to prevent them from being damaged by the molten glass. The oxygen atmosphere results in almost complete combustion, which is why the exhaust gases consist almost entirely of CO_2 and water vapor . This process is therefore the most promising for the development of potential CO_2 capture solutions (carbon capture) in the glass industry.

In addition to natural gas-fired furnaces, **all electric melting furnaces** are also already in use for some types of glass. These are currently used for the production of white glass or special glass, and in individual cases also for brown or green glass (currently only abroad, however). In modern furnace types, the electrodes are designed as top electrodes or in the shoulder of the side wall of the melting furnace. They protrude through the raw material cover into the melt, and the melting process runs vertically from top to bottom, whereby a closed raw material cover is necessary to prevent heat loss into the cold top furnace ("cold top"). The heat input from the top electrodes increases the temperature of the melt, which drives the melting process forward. Due to the higher temperature and convection velocity of the melt compared to conventional gas-fired furnaces, corrosion of the melting basin is increased. All electric furnaces therefore have a shorter lifetime of usually around five to six years and a maximum of eight years. On the other hand, the heat input is more efficient than in gas-heated furnaces. While burning kilns have efficiencies of 40 to 60 % in terms of fuel consumption, all electric melting furnaces achieve efficiencies of up to 95 %. These furnaces have so far been used primarily in the specialty glass sector and generally have a low capacity of approximately 10 to 100 tons per day, with some manufacturers achieving up to 180 tons per day. According to some glass furnace manufacturers, all electric glass furnaces could be restarted in individual cases, and only for certain glass products, in the event of a power failure (up to approx. 90 minutes max.) with production losses, but they would then have to overcompensate for the energy loss immediately afterwards in order to return to the original state of the melt. Upstream and downstream process steps would also have to be restarted and adjusted over a longer period of time. However, for high-quality products, especially specialty glass, these flexibilities are explicitly excluded. Section **Fehler! Verweisquelle konnte nicht gefunden werden.** takes a closer look at the expected effects on product quality.

5.1.2 Development of the Glass Melting Furnace Technology

According to statements by glass furnace manufacturers and in line with the assumptions of the BV Glas roadmap [1], three types of furnaces will play a particularly important role in the future.

Hybrid furnaces, which are powered by a combination of natural gas (or hydrogen in the future) and electricity, should be able to cover up to 80 % of the furnace's total energy requirements electrically in the long term. The aim is to achieve an electrical input corridor of 20 to 80 % of total energy consumption. As the electrical input increases, the furnace's total energy consumption decreases, as the electrical input is around 95 % more efficient than fossil fuel combustion. So far, this has achieved melting capacities of approximately 500 tons per day.

Despite the specified range, these furnaces are still designed for an optimal operating point in specific applications, as the power-to-fuel ratio has a significant influence on the furnace design: In conventional natural gas-fired furnaces, the flame burns in the upper furnace above the raw material mixture or the melt. As the electrical heat input increases through electrodes protruding into the melt from below, the remaining heat requirement to be provided by the flame decreases. This makes the upper furnace cooler. If the design/operating mode is incorrect or the current share is too high (above 50 to 70 %, and significantly earlier in the case of flat glass), the upper furnace may become cooler than the melt. In addition, the necessary minimum distance between two electrodes increases the size of the furnace, which means that a larger batch surface area must be covered by the flame. Both effects mean that the temperature distribution required for the desired glass quality can increasingly no longer be guaranteed. Some manufacturers offer an alternative furnace design in which the batch bed is covered by a flat ceiling to prevent "cooling down".

With lower electricity shares of less than 25 % and thus in transition to the already familiar boosting furnaces, the operation of the melting furnaces is also easier to control due to existing practical experience. Possible energy flexibility potentials through a conceivable variable energy source switch between electricity and gas are therefore primarily to be found in this area. A distinction must be made between reducing and increasing the proportion of electricity (and, conversely, the proportion of gas): In this area, it is easier to further reduce the proportion of electricity than to increase it. If the proportion of electricity exceeds 25 %, any further increase can only be carried out very slowly and cautiously, as otherwise bubbles will form on the electrodes. In extreme cases, this can lead to foaming on the surface of the melt, which acts as an insulator between the melt and the top furnace. The effect is exacerbated by the top furnace cooling down, and the foam increasingly seals the surface. In such a case, it takes several hours to return the melt to the desired state.

The fact that the energy input from gas firing is not equivalent to the electrical heat input is also evident from the viscosity of the glass melt. The raw material and cullet mixture loaded into the rear part of the furnace should be kept as compact as possible in the rear part of the furnace despite continuous replenishment. The very viscous melt in conventional (natural) gas-fired furnaces forms a convection roll that counteracts the movement of the batch and thus pushes the batch back into the rear part of the furnace. As described above, heating by electrodes leads to higher temperatures in the melt, which thus loses viscosity, weakening the return flow of the batch. If the unmelted batch gets too far into the front part of the furnace, the glass quality is compromised.

The aspects mentioned above mean that the theoretically conceivable energy flexibility potential of a hybrid melting furnace through a change of energy source can only be realized to a very limited extent in practice. For individual melting furnaces, it has been shown that a slight reduction in power supply of approximately 3 % for five minutes can be directly compensated for over ten minutes with 1.5 % above the initial level of electrical power , without jeopardizing the maintenance of the melt, but with changes in the melting properties and thus effects on product quality . In practice, however, a product change with adjustment of the hybrid parameters (current/gas ratio) is usually only carried out over days to weeks. A non-production-related adjustment of these parameters has been avoided in practice so far, but according to estimates by glass furnace manufacturers, it also takes place over a period of days to weeks. It can be assumed that these periods could be slightly shortened with increasing experience. Nevertheless, glass furnace manufacturers recommend keeping the optimal production point stable once it has been set in order to enable energy-efficient operation, not to jeopardize melting convection and product quality, and to extend the service life of the melting furnace. Melting furnaces for flat and specialty glass production are considered particularly sensitive, as the melt influences the shaping process. If the hybrid parameters need to be adjusted, this is only possible with product rejects and should ideally only be carried out over several days and, for example, at the same time as product changes.

Pure **hydrogen fired furnaces** are also being tested, for example in the ZeroCO2 project [8]. In the pilot project, a natural gas oxyfuel furnace is being converted to hydrogen oxyfuel and operated with a maximum power input of 50 to 80 %. However, the use of hydrogen is only feasible in container/bottle glass production in the foreseeable future. On the one hand, the heat density of the hydrogen flame is lower than that of the natural gas flame. On the other hand, the water vapor produced during combustion increases the $H_{(2)}O$ partial pressure above the melt and leads to contamination in flat glass production. The (purely) hydrogen-fired melting furnaces do not offer any relevant electrical energy flexibility potential compared to other furnace types. Furthermore, glass furnace manufacturers are reluctant to use hydrogen due to uncertainties regarding its economic availability.

Depending on the manufacturer, **all electric melting furnaces** are expected to have capacities of 300 to 400 tons per day. This scalability now needs to be proven in practice. It is technically limited by the minimum distances between the electrodes that must be maintained and the energy density distribution that can be achieved as a result. The necessary electrical infrastructure at the site must be upgraded accordingly, which involves high costs or construction subsidies, e. g. for transformers, switchgear, emergency power systems, etc. Another challenge in scaling all electric melting furnaces is the chemical composition of the raw materials and additives. Since the closed raw material cover means that a higher proportion of the refining gas, that would otherwise escape into the top furnace, is recycled in the melt, the addition of appropriate additives must also be adjusted.

Glass furnace manufacturers assume that all electric melting furnaces will initially be scaled up in the container glass sector before mature all electric technologies for flat glass production become available. According to furnace manufacturers, all electrified furnaces do not offer any energy flexibility potential in terms of the requirements of the Federal Grid Agency.

5.1.3 Common Ground and Conclusion of the Glass Furnace Manufacturers

It is currently not possible to predict whether one technology will prevail on the market and, if so, which one. The market and technology assessments of the melting furnace manufacturers are based on different developments. In addition to technical, product-specific requirements for capacity and quality, energy prices and connected loads are particularly decisive factors.

In order to maintain the glass melt with its convection currents and thus ensure the necessary dwell times and the desired glass quality, all furnace types, both in the status quo and in the future, must be continuously heated. This means that it is not possible to vary temperatures or adjust products and production quantities flexibly with any type of furnace. If parameters are not optimally set in the process, this usually results in at least one to two days of scrap production, depending on the type of glass. According to glass furnace manufacturers, various flexibility options have already been tested, but none have proven to be practical. New ideas are needed to address this issue.

However, hybrid melting furnaces offer theoretical energy flexibility potential due to the possibility of varying the ratio of electricity and gas as energy sources within given, narrow limits. However, the time axis for this is several hours, as the melt has high thermal inertia and a high average dwell time (approx. 24 hours on average for container glass). Large furnaces, which are more energy efficient due to their better surface-to-volume ratio, react more slowly than small furnaces, which are used, for example, in special glass production. Flexibility intervals, in terms of call-off durations and frequencies, are therefore only conceivable on a multi-day basis. In addition, switching between energy sources always has an impact on the service life of the furnace and reduces it.

Product changes can cause the furnaces to vary in melting capacity by +/- 10 %. This is already possible with electric boosting systems. However, due to the inertia of the process and the fact that the shape determines the removal from the melting furnace, boosting is only of limited use as a flexibility option.

As the most energy-intensive facility in glass production, the glass melting furnace therefore has low energy flexibility potential. Due to the inertia of the melt, adjustments can only be implemented slowly over time frames ranging from hours to days, or will be implementable in the future. This means that short- term responses to electricity prices are only possible to a very limited extent. Hybrid melting furnaces use both electricity and gaseous energy sources. However, adjusting the respective energy source ratios is only possible with long start-up and shutdown ramps in order to control the behavior of the glass melt, and is therefore only practical for seasonal adjustments.

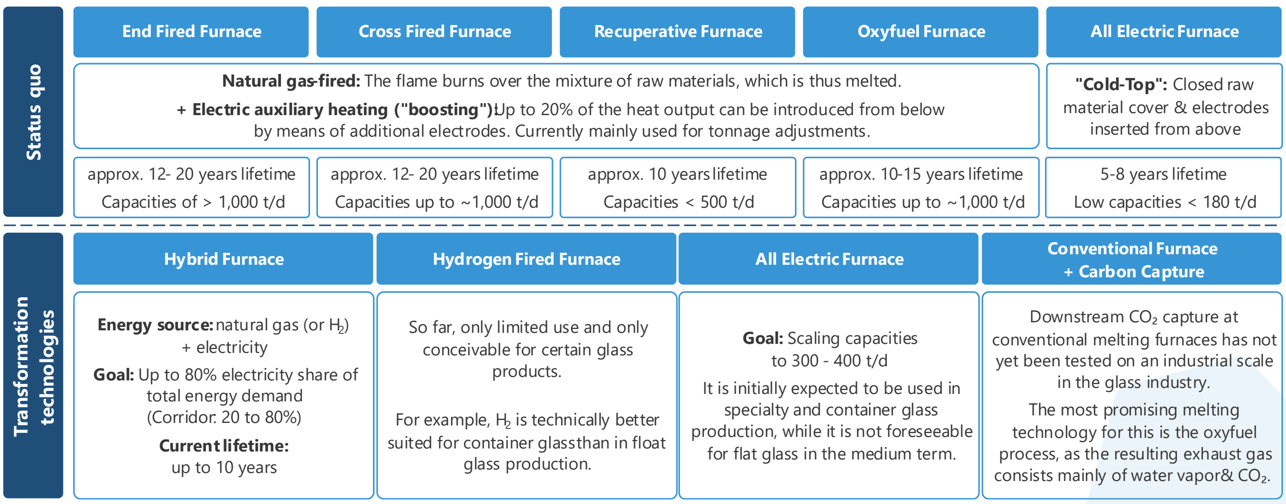

Figure 5-1: Simplified overview of melting furnaces in the status quo and possible transformation options.
In practice, lifetime and capacity depend heavily on the type of glass and product (see section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

5.2 Perspective of Glass Producers

The fundamental challenges in terms of energy flexibility are the same for producers in the flat glass, container glass, and specialty glass sub-sectors. Nevertheless, the individual processes differ from one another and each has its own requirements and characteristics, as indicated by the different properties of the melting furnaces used (Figure 5-2).

5.2.1 Flat Glass Production

In **flat glass production,** for example for windows, PV modules, or glass buildings, temperatures of up to 1,600 °C are required in the melt. After refining, the outlet temperature is approximately 1,100 °C. The liquid melt is then fed onto the float bath at approximately 800 to 1,000 °C for shaping. The glass leaves the bath at an outlet temperature of approximately 600 °C. The product is finally cooled in a controlled manner to approx. 60 to 70 °C in an electrically operated cooling furnace in order to reduce tension in the glass.

The melting furnaces currently in use have a capacity of 1,000 tons per day and a service life of approximately ten to twenty years, depending on the flat glass products manufactured. For many of these products, the melt can be supported by electrical boosting from below if the corresponding connected load is available at the site. According to current estimates, the maximum possible boosting support is approximately 20 % and has not yet been tested on an industrial scale. For some specific flat glass products, electrical boosting is not yet possible. Due to the required temperature distribution and necessary (convection) currents in the glass melt, a significant change in the additional electrical power is only possible over weeks, for example to prevent bubble formation. Compared to other glass products, flat glass production is subject to very high purity requirements in the range of 0.01 Gispen (bubbles) per 100 grams of product. On a daily basis, therefore, no significant energy flexibility is possible. Seasonal production planning would be conceivable, but the necessary adjustments would also take days to weeks, so that tonnage changes should be made as infrequently as possible. The use of hydrogen as a (supplementary) fuel is also not foreseeable in flat glass production due to the high quality and purity requirements, as the high H_2O partial pressure would lead to bubble formation in the glass in the tin bath.

Other electricity consumers include compressed air generators, which are mainly used for unloading raw materials. However, the associated energy quantities are very low, especially given the increasing share of electricity in glass production.

5.2.2 Container Glass Production

Container glass production in conventional melting furnaces is mainly powered by natural gas and up to 10 % electrical boosting. These furnaces could already be fired with up to 20 % hydrogen as an admixture, if available, and have a service life of approximately 15 to 18 years. The "NextGen Furnace" pilot plant [9] is also set to test the use of up to 80 % electricity; currently, around 60% is being achieved. After melting, the material is shaped using presses and compressed air injection. It is then heated to a maximum of 550 to 600 °C in a gas- or electrically-powered cooling furnace and cooled in a controlled manner over approximately 0.5-1.5 hours to relieve tension. Here, too, the process chain is fully integrated and must be operated continuously in order not to jeopardize temperature stability and thus product quality. Starting up new operating points in the melting furnace can take up to four weeks.

The hybrid melting furnace can theoretically vary between 20 and 80 % between electricity and gas without compromising product quality. However, adjustment takes several days to weeks and could therefore only be used for seasonal adjustments. According to the melting furnace manufacturers, switching from a high proportion of electricity to a high proportion of gas is possible in approx. 2 to 3 days, as described in section **Fehler! Verweisquelle konnte nicht gefunden werden.**, which is faster than switching in the other direction to a higher proportion of electricity. A proportion of 50% electricity can be achieved in approx. 8 to 10 days, with a further increase then usually taking weeks to months. A short-term reduction in electricity in the range of the control power (15 min) is possible in some cases, but must then be compensated for

Flachglas	Schmelzwannen mit Kapazitäten von bis zu 1.200 t pro Tag	Lebensdauer: ca. 14 – 20 Jahre
Behälterglas	Schmelzwannen mit Kapazitäten von ~ 50 - 500 t pro Tag	Lebensdauer: ca. 10 – 18 Jahre
Spezialglas	i.d.R. kleinere Kapazitäten von ~ 40 kg bis 160 t pro Tag	Lebensdauer: ca. 4 - 6 Jahre

Figure 5-2: Status quo: Furnace properties by glass product group.

electrically over a longer period of time beyond normal operation or overcompensated by additional firing, and is generally avoided due to quality concerns. The transferability of this energy flexibility option to other areas of glass production has not yet been tested. Compared to the service life of conventional melting furnaces of approximately 10 to 18 years, the target service life for hybrid melting furnaces in the container glass sector is 10 years.

All electric furnaces have a shorter service life of approximately eight years when operated continuously and linearly due to the different flow conditions and, in some cases, higher temperatures in the melt. However, they do not offer any energy flexibility potential, as continuous heat input is necessary to maintain the melt and electricity is the only energy source available. With a reduction in the electricity supply of up to 15 minutes, it is possible to readjust the melt, but this always involves production waste, and each adjustment of the operating point further shortens the service life of the furnace. In addition, not all large transformers are currently designed for flexible control and can be damaged by reduced operation. However, flexible large transformers are available on the market [10].

As a rule, the core processes and production lines of glass manufacturing account for over 90% of the total energy requirements of the sites. The largest other consumers of electricity are compressed air compressors, vacuum generation, and/or electric cooling furnaces. Since all processes must be available in a time-critical manner for production, there is no significant energy flexibility potential either.

5.2.3 Speciality Glass Production

For **specialty glass production,** all types of furnaces (oxyfuel, regenerative furnaces, all electric furnaces, and hybrid types) are used depending on the requirements of the glass to be melted. The furnaces are generally smaller, with a capacity of approx. 40 kg to 160 t per day, and have a service life of 4 to 6 years due to the more chemically aggressive raw materials and higher melting temperatures of approx. 1,700 °C. Here, too, the entire process, from raw material preparation to glass melting, drawing and forming, and post-processing, is integrated and continuous. The sub-processes must be controlled to within a few °C (in some cases to within 0.1 K) in order to meet both glass quality requirements and forming process tolerances in the hundredth of a millimeter range. These requirements are significantly more demanding in the specialty glass sector than in other sub-sectors. In free-form processes, e.g., in the production of tubular glass as a starting material for the manufacture of pharmaceutical primary packaging, the geometry is determined solely by the constancy of the mass flow of the glass, the temperature-dependent viscosity of the liquid glass melt, and constant process conditions. The entire process is very sensitive to changes in the process parameters. Even a few minutes of power failure can result in at least one day of production loss. Due to the process-related long dwell times of approximately three to five days in the melting furnace and the long dead times until a new thermodynamic equilibrium is established when process parameters are adjusted, all process changes or disruptions have an impact over a period of more than a week.

Hybrid melting furnaces are currently used primarily for colored glass and have a ratio of approximately 30 % electricity to 70 % natural gas. Practical trials have already been carried out in the Kopernikus SynErgie project, but these show negligible potential if glass quality is not to be compromised. All electric systems are also possible for selected specialty glass products. However, these do not offer any energy flexibility potential .

The possibility of providing minute reserves through smelting plants was also investigated. Implementation was not possible because the boundary conditions (minimum output, provision duration) could not be met. Emergency power generators could be used in some production facilities to participate in the provision of minute reserves and, in some cases, secondary reserves by third parties. Seasonal energy flexibility options are not feasible in the specialty glass industry because specific market and customer requirements must be met in a timely manner.

5.2.4 Ancillary Processes and Storages

In the upstream and downstream processes of glass production, electrical solutions are already becoming increasingly prevalent where available due to their greater efficiency. For example, (hybrid) electrical solutions already exist for air and batch preheating, which is currently usually carried out using combustion exhaust air. For cooling furnaces, the electric version is the best available technology according to the current state of the art, but fossil-fuel-powered cooling tracks still predominate at present. For other process steps, such as pre-hardening or shrinking, the electrical options are not yet available or are not yet economically viable. Other processes with electrical energy flexibility potentials are increasingly coming from heat pumps for building heating. However, as melting processes become increasingly electrified, this share of total electricity consumption is becoming irrelevant.

PV self-generation plays a minor role for glass production sites due to the limited space and yield potential available at compared to the current and future energy requirements of the sites . Nevertheless, it should be noted that on-site self-generation generally counteracts market-driven energy flexibility incentives: If (day-ahead) price signals are used to encourage industrial customers to consume more electricity at low prices during lunchtime, this corresponds exactly to the time windows in which on-site generation is also primarily used for own consumption, thereby reducing grid consumption – albeit only slightly in comparison to total energy demand.

Regardless of the processes already in place or those that will be required for glass production in the future, it is possible to install energy storage facilities at the respective production sites in order to balance flexible electricity procurement and ensure continuous production. In the glass industry, there are two options for this, both of which have been discussed with glass producers. Glass producers view the **in-house production of hydrogen** for storage and use in the process or for reconversion into electricity as critical and impractical due to the associated legal requirements for green hydrogen under the European Renewable Energy Directive (RED) and the lack of expertise in electrolysis operations. There is greater willingness to consider **battery storage**, but this is also associated with serious concerns. Depending on the economic and regulatory framework, it would be necessary to examine on a case-by-case basis whether a battery storage facility could be operated economically at the site and at the same time provide the expected energy flexibility services. Market-oriented operation and electricity (arbitrage) trading [1] are not yet a (core) business area for glass manufacturers, who generally make long-term electricity purchases. In addition to the economic conditions, site-specific circumstances must also be taken into account. Historically grown glass production sites in particular often lack the space for separate, decentralized battery storage solutions. In addition, the internal and upstream grid infrastructure would have to be upgraded in order to adequately cover both the expected high level of electrification in glass production in the future and the charging cycles of the battery storage system in terms of energy requirements and connected load. The corresponding grid expansion and connection periods must be taken into account. If the techno-economic conditions for a battery storage facility at the site are met, a storage facility increases security of supply.

5.2.5 Common Ground and Conclusion of the Glass Producers

Despite differences in the details of the individual glass production processes, all sub-sectors have in common that both the core processes and the subsequent shaping must be carried out continuously and without fluctuations in the energy source composition and temperature. The processing steps (shaping, cooling) must be carried out immediately afterwards, while the melt or glass drops are still malleable and follow strict temperature gradients, in order to avoid tension in the product. Therefore, no intermediate storage is possible in the production process.

Furthermore, production facilities in all areas are only economical if they are operated at almost full capacity and continuously. In addition, there is competition with two other objectives: On the one hand, flexible operation or frequent adjustments to production lead to a decrease in energy efficiency. On the other hand, the goal of greenhouse gas neutrality requires increased electrification of glass production. This is accompanied by a higher, more consistent power consumption with a correspondingly higher connected load.

According to the companies, on-site energy storage, e. g. using battery storages, has so far been uneconomical due to the size of the required energy quantities. In addition, the infrastructure on site often needs to be upgraded for this purpose. The complexity and control of the energy infrastructure at the site increases due to the integration of storage facilities, PV plants, and all electric furnaces, if applicable. As with the potential self-generation of hydrogen, operating battery storage facilities with the necessary marketing expertise is not a core competence of glass manufacturers.

Even with existing technical energy flexibility, the electricity purchasing of glass producers does not allow for a significant response to short-term price signals, for example on the spot market: In order to prevent the risk of high, short-term price fluctuations while ensuring the necessary continuous power supply to production facilities, the majority of electricity is purchased on a long-term basis several years in advance (hedging).

In conclusion, it should be noted that differences between products, melting furnaces, and locations do not allow the findings to be automatically transferred from one glass production site to all others, and that the specific requirements and framework conditions must be taken into account in each case.

[1] Electricity arbitrage trading refers to the targeted purchase and sale of electrical energy at different times in order to profit from price fluctuations (price spreads) on the electricity market. Electricity is purchased cheaply when prices are low (e.g., when there is a high feed-in of renewable energies) and sold at a higher price when demand rises and prices are correspondingly higher.

6 Discussion and Outlook

The transformation of the glass industry is leading to increasing electrification. The scaling of the relevant technologies is not yet complete, but is not expected to lead to any relevant energy flexibility potential. Battery storage could create energy flexibility potential outside of actual glass production, but is not always compatible with site-specific conditions.

The transformation of the glass industry is accompanied by a high degree of electrification. The current electricity demand of 3.8 TWh [11] will more than double, depending on the transformation path. Fully electric solutions are not yet available for all glass melting tanks or products, or are currently still being scaled up. Energy efficiency, melting capacity, and product quality are the relevant variables in the development of hybrid or all electric melting tanks. Increasing energy flexibility potential is not to be expected for these melting tanks in the , as the heat input must continue to be constant.

With increasing electrification, the corresponding connection capacities at the sites must be expanded in order to operate the continuous glass melting process, which is both economically and technically necessary. If battery storage facilities are set up and operated at the site, this opens up opportunities for exploiting energy flexibility potential, but at the same time entails a further significant increase in the site's connection capacity. In this case, glass producers must build up expertise outside their core business in order to operate the storage facility economically and in a market-oriented manner. It is questionable whether market-oriented operation of the storage facility based on day-ahead prices is always beneficial to the grid.

From the perspective and based on the experience of glass tank manufacturers and glass producers, the energy flexibility potential in the glass melting process is limited for technical reasons. Corresponding flexibility incentives therefore have no effect. In the energy-intensive process of glass manufacturing, energy efficiency is an important factor for economically competitive glass production. Adjustments to the melting process not only jeopardize product quality, but also always reduce energy efficiency.

Conclusions for regulation

The increasing share of fluctuating electricity generation in the energy system can be offset by tapping into energy flexibility potential. In terms of security of supply and the increasing integration of renewable electricity generators into the energy system, it therefore makes sense from a systemic perspective to incentivize theoretically available energy flexibility potential. However, when designing these incentives, the technical limitations and characteristics of the various processes under consideration must be taken into account. Energy-intensive glass production, which will become increasingly electrified in the future, must be operated continuously in order to maintain the melt and prevent damage to the melting tanks. The very low potential for load shifting, i.e., a load reduction with immediate (over)compensation, which is only conceivable for a few glass processes and only for a short period of time, is not suitable for balancing day-night cycles. It always causes product waste and carries the risk of having to readjust the melt over a period of hours or days. Regulatory incentives aimed at activating energy flexibility potential that is practically impossible to implement therefore do not achieve the desired effect.

Outside the core process, battery storage offers the greatest opportunity to provide energy flexibility potential. However, the respective individual site conditions, such as connected load, internal electrical infrastructure, or space requirements, must be taken into account and lead to considerable restrictions on this option. Aspects such as the duration and complexity of the approval process, investment subsidies, or the time required to provide the connected load play a decisive role in every location-specific investment decision. A more system-friendly alternative could be larger, central battery storage facilities outside the production sites, for example at grid nodes. In any case, framework conditions must be created for the economically viable operation of battery storage facilities from the perspective of the players involved, while at the same time ensuring that their use is systemically sensible .

Key Findings of the Study

1

Diversity in glass manufacturing
Each location and each product in the glass industry has its own highly individual requirements and conditions for achieving the desired product quality. It is particularly important to distinguish between the individual sub-sectors of flat glass, hollow/container glass and speciality glass.

2

Technical reasons: Low energy flexibility potential in the manufacturing process
All glass production processes must run continuously in order to maintain the set thermal equilibrium in the process and thus the desired product quality. Changes to the process have a direct impact on product quality and usually lead to production rejects. Due to the thermal inertia in the process and the sometimes long dwell times in the melt, it takes several days to weeks to adjust operating points and obtain a usable product that meets quality requirements.

3

Decarbonization: Rising electricity consumption, consistently low energy flexibility potential
The decarbonization of the glass industry is based primarily on increased electrification, either through all electric or hybrid melting furnaces. Both technologies significantly increase the electricity consumption of production sites. However, the processes must continue to be operated continuously and without significant energy flexibility potential in order to maintain product quality. The elimination of band load privileges makes electricity procurement considerably more expensive and, especially in the case of hybrid melting tanks, means that the use of fossil natural gas is the more economical option. The goal of decarbonization should be prioritized and supported by appropriate incentives, including in the grid fee system.

4

Flexibility vs. efficiency, service life and economic utilization
Adjustments to the operating points of the melting tank usually take hours to days, and in some cases weeks. Each adjustment is associated with product waste and reduces the service life of the melting tanks and, in some cases, the transformers. In order to operate a melting tank economically, it must be continuously utilized under full load for as long as possible. Any adjustment of the operating point also reduces the energy efficiency of the melting tank. Hybrid melting tanks in particular are designed for maximum efficiency, both in terms of their tank size for the planned number of electrodes and in terms of the size of the top furnace for the associated gas flame, in accordance with an optimum operating point.

5

Costs and economic risks in electricity procurement
The costs incurred by the elimination of baseload privileges cannot be offset by alternative revenue opportunities, such as conceivable marketing on the control energy market. The technically feasible energy flexibility potential for providing the corresponding power is too low for this. In addition, baseload supply is often secured several years in advance through long-term electricity purchases, depending on the risk appetite of glass producers, in order to hedge against price risks, with only a small portion being procured at short notice via the spot market. In order to be able to react to price signals, electricity procurement would have to be more strongly oriented towards the spot market, which would lead to a greater risk of dependence on short-term price fluctuations. Since the processes must be operated continuously and do not offer any relevant energy flexibility potential, electricity would then also have to be purchased even if prices were high in the short term.

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