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Technical Guidelines on
Energy Efficiency in Major Energy-Consuming Sectors

Energy Efficiency in the Glass Fiber Industry

Deutsche Gesellschaft
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Zusammenarbeit (GIZ) GmbH

Imprint

The report "Energy Efficiency in the Glass Fiber Industry - Technical Guidelines on Energy Efficiency in Major Energy-Consuming Sectors" is published within the framework of the "Sino-German Demonstration Project on Energy Efficiency in Industry." The demonstration project, as part of the Sino-German Energy Partnership between the German Federal Ministry for Economic Affairs and Climate Action (BMWK) and the National Development and Reform Commission (NDRC), jointly implemented by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH and the National Energy Conservation Center (NECC), aims at carbon emissions reduction in China's major energy-consuming sectors by providing energy efficiency measures and best practices, and strengthening private sector cooperation. The report is co-financed by the "Supporting Low Carbon Development in Jiangsu Province Project (Phase III)," which is funded by BMWK's International Climate Initiative (IKI) and jointly implemented by Jiangsu Department for Ecology and Environment and GIZ. As a German federal enterprise, GIZ supports the German government in the achievement of its goals in international cooperation for sustainable development.

This report is the fourth in a series of publications to provide an overview and analysis of energy efficiency measures for key sectors including airports, and the manufacturing industries for pulp and paper, cement, ceramics, and glass fibers, drawing from German and international experiences and best practices.

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Foreword

Dear readers, colleagues and friends,

Despite major global challenges, we have seen substantial progress in the energy transition in Germany and China in the last years. China remains the country with the world's largest installed capacity of renewable energy, whereas in Germany, the share of renewables in the net electricity generation has exceeded 50% for the first time. But whilst the promotion and development of renewable energy plays an important role in our global measures to mitigate the negative impact of climate change, it alone would not be sufficient to protect a liveable future for humanity. To complete the necessary energy transition, it is crucial to improve energy efficiency in order to reduce greenhouse gas emissions in industry, buildings, and transport. Focusing on improving energy efficiency in industrial production is especially powerful, since industry is one of the major energy consuming segments worldwide, making up roughly 29% of total final energy consumption.

As part of its energy transition, the German Federal Government has set itself the target to reach climate-neutrality in all sectors by 2045. By mid-century, Germany aims to cut its primary energy consumption by 50% compared to 2008. To achieve this, Germany adopted the "efficiency first" principle, which aims at prioritising energy efficiency wherever possible.

In a similar vein, China has emphasised energy efficiency as part of its Energy Revolution Strategy (2016– 2030). The 14th Five-Year-Plan set forth by the Chinese government aims to reduce energy intensity by 13.5% and carbon intensity by 18% over the 2021-2025 period. These targets are set against the backdrop of bringing carbon emissions to a peak before 2030 and achieving carbon-neutrality by 2060. To meet these ambitious goals, comprehensive reforms in industries are needed.

The glass fibre industry is an energy-intensive sector, its unit energy consumption ranging between 7.2 to 12.6 GJ per tonne of glass product. A variety of measures – from glass recycling to using green hydrogen, heat recovery and electrification – are available for reducing fossil fuel consumption and carbon dioxide emissions in the sector. Notably, 15-25% of the overall CO2 emissions in glass production are process emissions, i.e., they stem from chemical reactions in the raw material itself and cannot be avoided with conventional matters. A full decarbonisation of the glass fibre sector will hence also require the deployment of innovative technologies such as carbon capture and storage.

Here, international cooperation between Germany and China can play a contributing role. This report is published as part of the Sino-German Energy Partnership between the German Federal Ministry for Economic Affairs and Climate Action (BMWK), the National Development and Reform Commission (NDRC) and the National Energy Administration of the PRC (NEA), and the project "Supporting Low Carbon Development in Jiangsu Province Phase III" funded by the German Federal Government's International Climate Initiative (IKI).

The report is the fourth in a series of reports on energy efficiency measures in heavy industry sectors. It highlights process-related measures in the very energy-intensive process of glass fibre production – with a focus on the production of continuous fibre filaments – and discusses these according to their implementation potential and effectiveness.

I would like to express my gratitude to all involved experts and implementing partners, especially the National Energy Conservation Center of China (NECC) and the Jiangsu Department for Ecology and Environment, for their ongoing support. I sincerely hope that this study will trigger inspiration and contribute towards finding more energy-efficient solutions that lead us to a cleaner future.

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Content

List of Figures

List of Tables

Abbreviations

BAT	Best Available Technology
BM	Benchmark
BREF	Best Available Technologies Reference Documents
CaO	Calcium Oxide
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CFF	Continuous Filament Fibres
EEA	European Environment Agency
ETS	Emissions Trading System
EU	European Union
FEM	Finite Element Models
GAE	Glass Alliance Europe
GHG	Greenhouse Gas
GJ	Gigajoule
IEA	International Energy Agency
IGES	Institute for Global Environmental Strategies
IPI	Industrial Production Index
ISO	International Standards Organization
JRC	Joint Research Centre
kWh	Kilowatt hour
LAGA	Bund/Länder-Arbeitsgemeinschaft Abfall (Working Group Waste - Germany)
MBPC	Model based predictive control systems
MJ	Megajoule
Mt	Million tonne
Mg	Mega-Gramm (identical to one tonne)
MWh	Megawatt hour
NGO	Non-Governmental Organization
O&M	Operation and Maintenance
ODEX	Objective of the Energy Efficiency Index
PEM	Polymer Electrolyte Membrane
PI	Proportional and Integral
PID	Proportional Integral Derivative
PtX	Power-to-X technologies
R&D	Research and Development

RFG	Recycled Flue Gas
SCADA	Supervisory Control and Data Acquisition
SOEC	Solid Oxide Electrolysis Cell
TCR	Thermo Catalytic Reforming
TFC	Total Final Consumption
TRL	Technology Readiness Level
UNEP	United Nations Environment Programme
WHR	Waste Heat Recovery

1

Executive Summary

Energy efficiency improvements in the industrial sector are a powerful and efficient means to reduce overall energy consumption and greenhouse gas emissions given the following facts:

- **Large shares of TFC** (total final energy consumption) **attributable to the industrial sector**, corresponding to 28.6 % (world average) and even 48.3 % (China) (IEA, IEA data and statistics, 2018),
- Prevailing large shares of **fossil fuel in industrial energy consumption** (TCF) – both worldwide (10 % oil products, 20 % natural gas, almost 30 % coal) and in China (roughly 5 % oil products, 7 % natural gas, 50 % coal) (IEA, IEA data and statistics, 2018),
- Considerable leverage effects due **to relatively few actors** in the industrial sector (large energy savings can be achieved by one single industrial company, in contrast to measures targeting other sectors),
- Current potential of considerably high levels of **untapped energy efficiency**, and
- **Additional benefits**: increased competitiveness, smoother production, less down time, positive impacts on efficiency covering all resources: water, air, soil and materials.

In Europe, the most successful range of measures for energy efficiency improvement comprises the application of benchmark values, both for the permission of new installations (see also Best Available Technologies as referred to in the **BAT documents**), and the determination of reference values for the share of free allocation in the **European Emission Trading Scheme**. The EU ETS is a cap-and-trade system in place since 2005. It currently covers about 11,000 heavy energy users including power stations, industrial plants and airlines, together responsible for about 40 % of overall carbon emissions in the participating countries. Preliminary results show that so far, the scheme has significantly contributed to overall emission reductions and led to reductions by approximately 35 % in the period 2005 - 2019. Further efforts are required to reach the overall goal of GHG reduction by 55 % by 2030, as defined in the European Green Deal. Another important policy instrument which leads to continuous improvement of (industrial) processes is the obligation of large enterprises to perform external energy audits every four years or alternatively implement an energy or environmental management system following the requirements of the **Energy Efficiency Directive** (Directive 202/27/EU and its amendment in 2018).

Energy efficiency measures range from “simple” good housekeeping and the use of control systems (both of which are prerequisites for the following measures) to equipment change, process integration and application of alternative processes. The following guideline focuses on process-related measures for the **glass fibre industry**. The selection of these measures is based on their achievable potential/applicability (with focus on China) as well as their effectiveness (necessary changes / investment costs in comparison to achievable benefit). Data sources include not only international and local studies/analysis but also estimations based on experts’ experiences.

The definition of “**glass fibre**” industry is not always applied uniformly. Mostly it comprises continuous fibre filaments (CFF), sometimes also the production of glass wool and rock wool. CFF is produced and supplied in a variety of forms: roving, mat, chopped strand, textile (yarn), tissue, and milled fibre. The main end use (approximately 90 %) is the production of composite materials (glass-reinforced plastic, GRP), by reinforcement of both thermosetting and thermoplastics resins.

The present report concentrates on CFF production and also discusses major energy related issues which are common to all glass production facilities, which include the production of flat glass and bottle glass. In Europe, only about **0.8 million tonnes** of glass fibre are produced, which corresponds to less than 3% of overall glass production.

Unit energy consumption per tonne of glass fibre in Europe is 2 MWh of which around 80% is attributable to the sub-process of melting and fining.

This guideline comprises all process steps performed for the production of glass fibres, including batch preparation, melting and fining, forming and finishing.

The following energy efficiency measures were identified as the most promising ones and are described in detail in this guideline:

- Optimized Fluxing Agents,
- Glass Fibre Recycling,
- Oxy-Fuel - Synthetic Air,
- Oxy-Fuel Furnaces Regenerative (Eco-HeatOx),
- Electric Melting, Electric Boosting,
- Batch and Cullet Preheating,
- Low Carbon Fuels (H2, O2),
- Model Based Predictive Control (MBPC),
- Pressure Drop Minimization.

Evaluating energy efficiency potentials in terms of changing final energy consumption (electricity and thermal energy) must always be seen in close connection with relevance to **GHG emission reduction**. This means that the actual GHG reduction impact strongly depends on the **actual fuel replaced** and the energy source used for electricity production. This fact especially refers to all fuel switch projects and the measure of replacing fossil fuelled furnaces by electric furnaces. With the current predominantly high grid emission factors for electricity, the switch to electric furnaces leads to a negative CO2 balance. However, the result can change considerably with low emission electricity sources.

Apart from currently established technologies and CO2 abatement strategies such as heat recovery, process optimisation and increased use of cullet, additional efforts are required to achieve a larger scale of decarbonisation. In the long run, major contributions to CO2 reduction are expected from carbon capture technologies and from the use of hydrogen, syngas and biogas.

Energy and CO2 savings are calculated based on specific assumptions (shown at the respective section) and – if not otherwise specified – on IPCC emission factors for gas (0.202 t CO2/MWh), coal (0.335 t CO2/MWh) as well as on the Chinese average grid emission factor of 0.618 t CO2/MWh taken from the IGES database. (https://www.iges.or.jp/en/pub/list-grid-emission-factor/en)

The following charts summarize the expectable energy savings and resulting net CO2 savings. Pressure Drop Minimization leads to comparably small reductions which cannot be depicted in the below scale.

Figure 1: Energy Saving Potentials of Selected Measures (kWh/t)

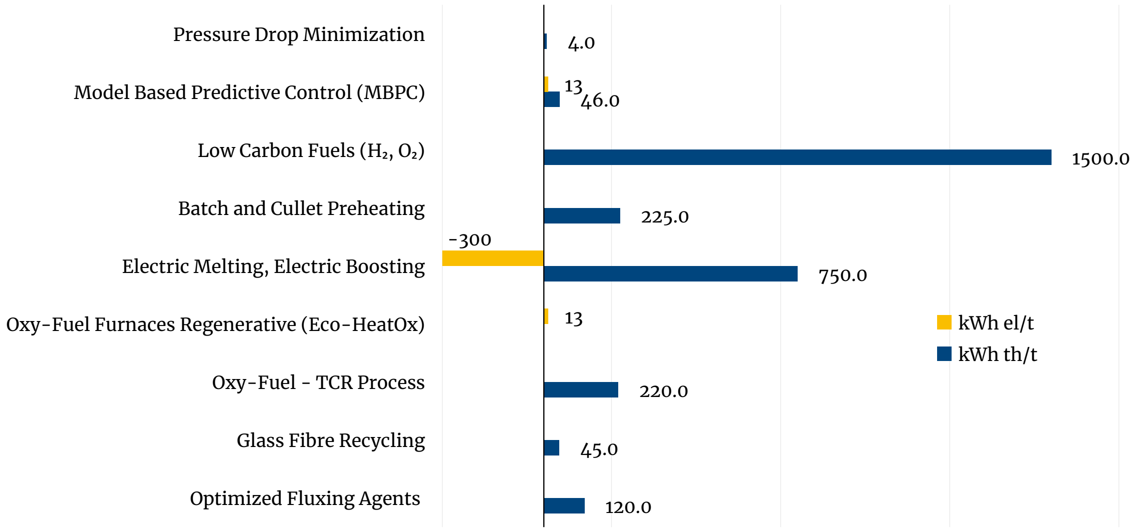
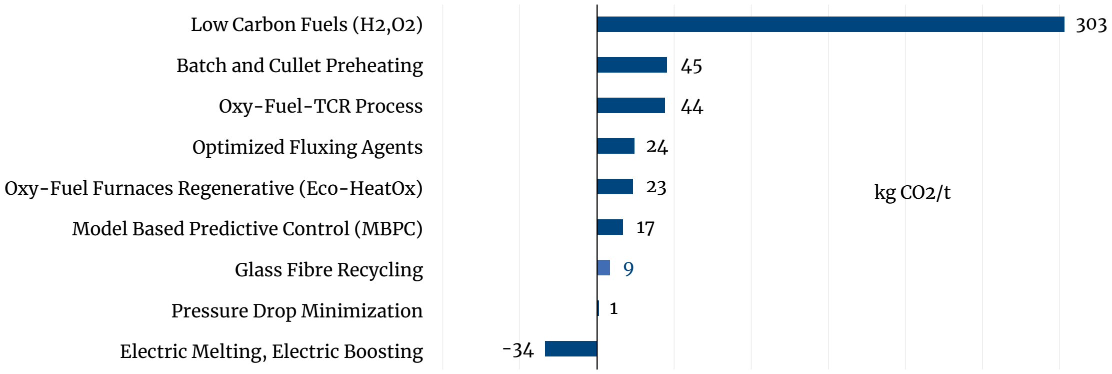


Figure 2: Net CO2 Saving (kg CO2/t) Potentials of Selected Measures[1]



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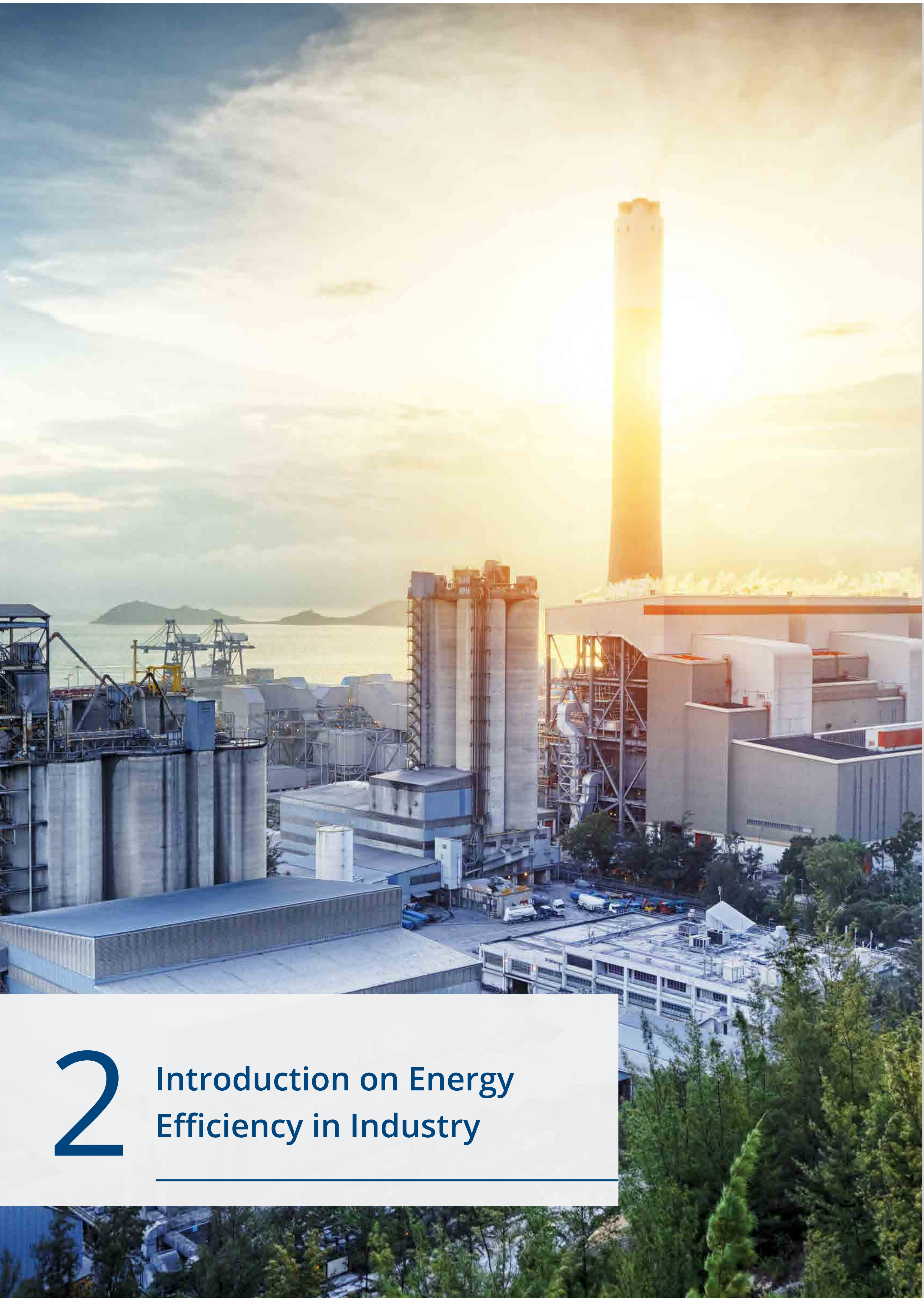
[1] Currently negative saving of electric boosting due to emissions of power generation.



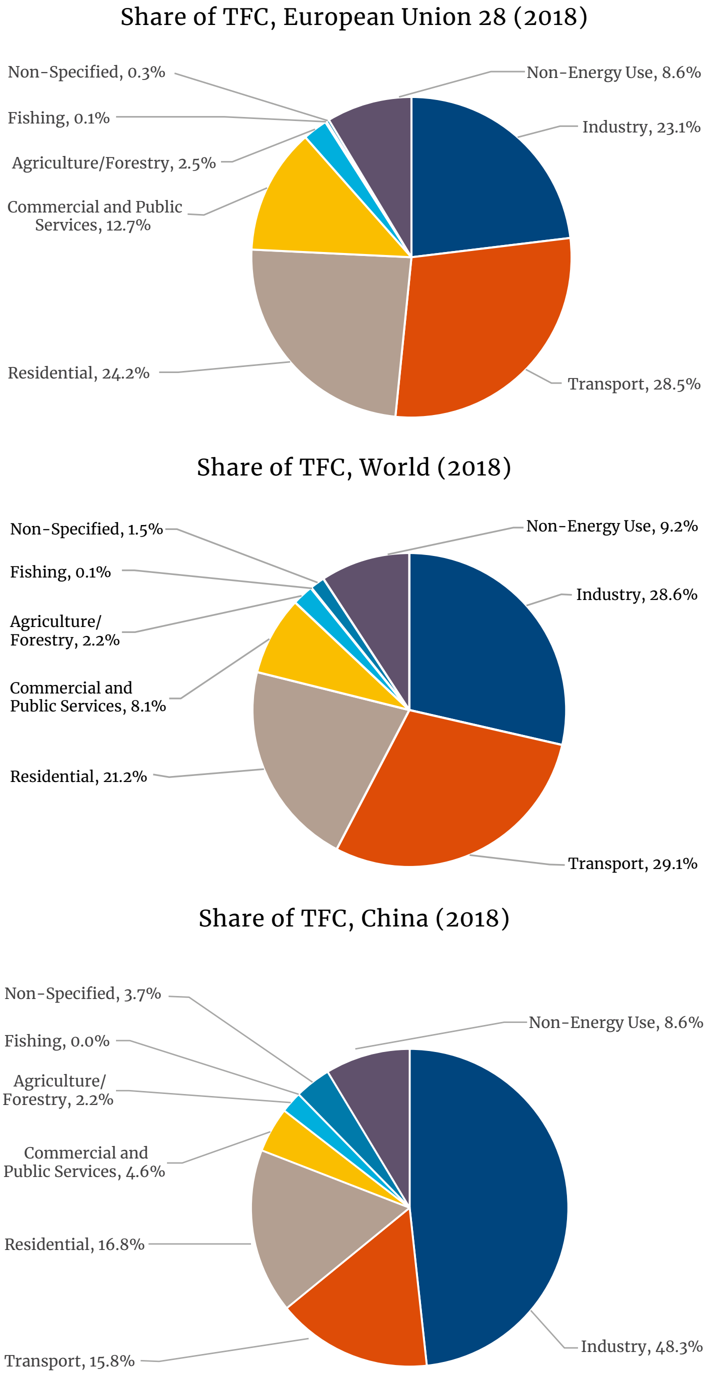
2

Introduction on Energy Efficiency in Industry

2.1 Description of Baseline Situation and Energy Consumption

Industry is one of the **major energy consuming sectors** worldwide. This is shown in the following charts depicting the Total Final Consumption (=TFC) shares:

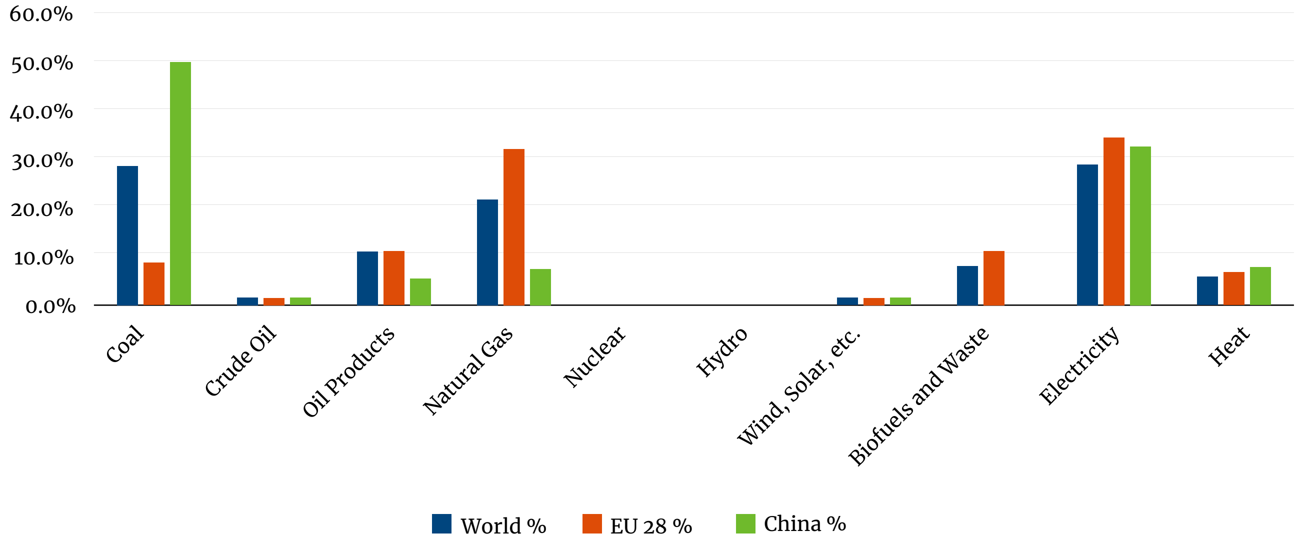
Figure 3: TFC Shares: Top left EU, Top right World, Bottom China



Source: (IEA, IEA data and statistics, 2018)

Regarding energy sources used in industry, the relative importance of different energy sources varies considerably among countries - especially with respect to coal and natural gas.

Figure 4: TFC Shares / Industry



Source: (IEA, IEA data and statistics, 2018)

Energy efficiency in industry is considered to be one of the most powerful measures to reduce overall energy consumption and GHG emissions – not only due to the size and importance of the industrial sector, but also because there are relatively few actors in comparison to other sectors. Thus, efficiency changes in one plant lead to comparatively large savings.

In the European Union, industrial energy consumption has been decreasing considerably since 2007. However, more than half of the reduction was due to a decrease in the overall industrial activity caused by the recession. **Energy efficiency has improved in the last years** (at rates at about 1 % per year), but is still at a lower level than in the early 2000s. This can be partly explained by large equipment not operating at full capacity – and thus less efficiently – as well as by the fact that part of energy consumption is relatively fixed and not related to production levels. (Fraunhofer ISI, 2018)

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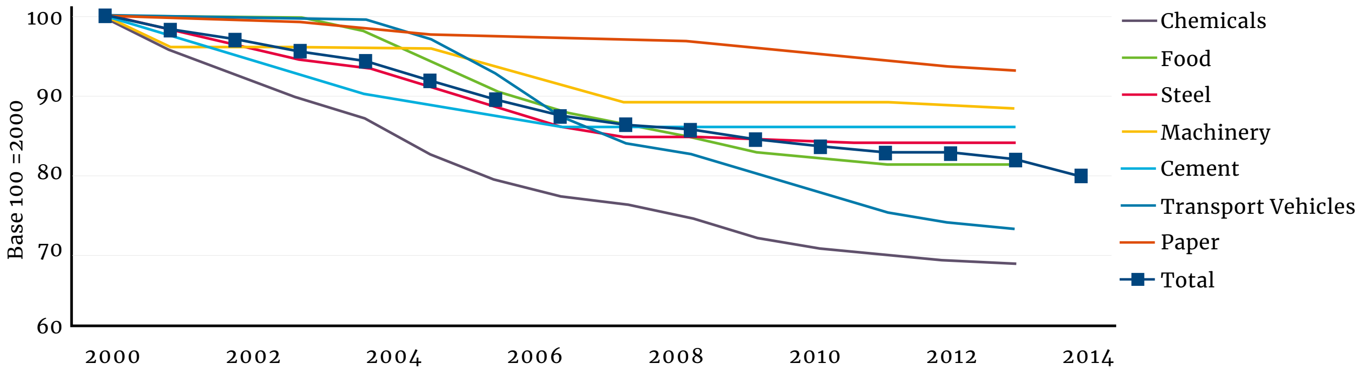
[2] "ODEX" (objective of the energy efficiency index) is derived at sector level (household, industry, transport) and weighs the indices of specific consumption by sub-sector (or end-use) with the share of each sub-sector in the sector's energy consumption. In the industry sector, ODEX is derived at the level of 14 branches based on specific consumption per tonne for steel, cement and paper and consumption per IPI (industrial production index) for other branches.

Overall energy efficiency progress can be measured via different indicators. One of them is the ODEX indicator[2] which measures energy consumption (physical, not financial) by production activity at sector level.

This indicator is used for different industrial sub-sectors in the European Union and shown in the following graph.

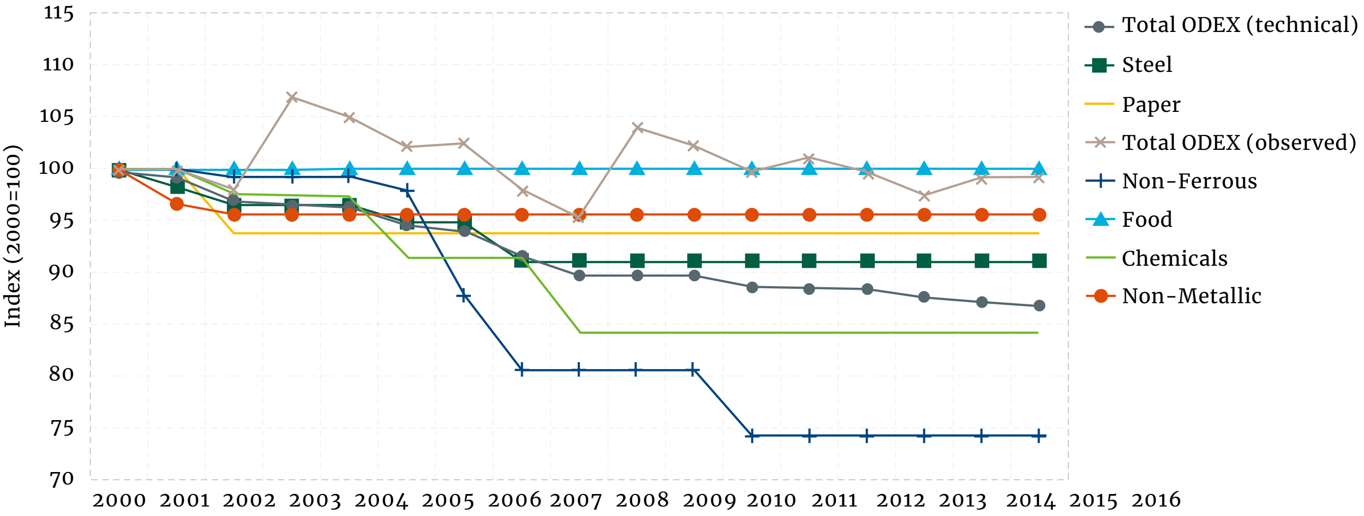
Figure 5: ODEX Indicator- Industrial Sectors European Union



Source: (Bruno Lapillonne, 2018)

It is clear that the overall energy efficiency has been improving by about 1.4 % per year since 2000 (or by 17 % cumulatively since 2000). However, the rate of improvement slowed down since the economic crisis. In Germany, for example, this effect is more noticeable:

Figure 6: ODEX Indicator- Industrial Sectors Germany



Source: (Fraunhofer ISI, 2018)

There are several studies referring to **considerable potential of energy efficiency currently available worldwide.** E.g., a study from IEA (2007) cited in the UNEP Best Practices and Case Studies Analysis shows an overall potential summing up to 600-900 Mtoe/year and 1,900–3,200 Mt CO2 savings per year based on commercial, cost-effective proven technologies. (Fawkes, 2016). These figures correspond to global improvement potentials of around 18 - 26 % of global industrial energy uses and 19 – 32 % of global CO2 emissions in the industrial sector. The highest potentials are expected to be in the chemicals, iron and steel, cement and pulp and paper sectors.

2.2 Energy Efficiency Policy and Management

In general, policy options can be categorized as "**carrots**" (incentives which make the desired action more attractive, in this case increasing energy efficiency) and "**sticks**" (penalties for companies not complying with relevant targets). These policy options can take the form of regulatory measures, fiscal/financial policies and information/capacity building (Fawkes, 2016). In the industrial sector in Europe, the most important tools and measures are the definition of Best Available Technologies, the European Emission Trading scheme and the obligation to apply energy auditing.

There are different energy consumption/energy efficiency figures in the same industry's different production sites, depending on the applied technologies, the size of the plant and its operation. One of the most powerful methods of examining different production sites is to compare their actual consumption with sectoral energy benchmarks and – more globally – their respective distance to **Best Available Technologies (BAT)**.

In Europe, for example, there are reference documents describing Best Available Technologies for industrial sub-sectors, called BREFs, which follow the requirements of the EU Industrial Emission Directive[3]. The results, cover not only the energy consumption performance but also the relevance for emissions to air, water and soil as well as resource efficiency. They are derived from discussions between industry representatives, NGOs, the EU Member States and the European Commission and are published on the website of the European IPPC Bureau under https://eippcb.jrc.ec.europa.eu/reference. According to these results, new installations have to comply with BAT standard[4] and corresponding emission levels from the start of operation. Existing installations have to be adapted within 4 years after publication of BAT conclusions.

Another application of benchmarking against the most efficient industrial plants can be found within the **European Union Emission Trading Scheme**, which has been operating since 2005. Designed as a cap-and-trade system, this market-based mechanism aims to reduce overall GHG emissions in the most cost-effective way. This means that a specific cap is defined for all covered installations (currently about 11,000 heavy energy-using installations including power stations & industrial plants and airlines operating between these countries) which together are responsible for about 40 % of overall emissions of the participating countries[5]. This cap defines the total amount of greenhouse gases which can be emitted by all installations covered by the system. The "emission allowances" have to be surrendered each year by the companies to fully cover their actual emissions. Some of the allowances are allocated to companies via a mechanism that takes into account historical emissions of the respective sector and emission levels of the best 10% participating companies (benchmarking), amongst other factors. The difference (either surplus or lack) can be traded on the market.

Preliminary results show that the scheme reaches its targets. Emissions of the **covered installations were reduced by about 35 % over the period 2005 to 2019**. In order to achieve a higher and more robust carbon price, the "Market Stability Reserve" was introduced in 2019. Following the **European Green Deal**[6], the EU targets an overall GHG emission **reduction of 55 % by 2030**. Within this package, energy efficiency was specified as the first key objective because it was considered to be one of the easiest ways to reduce greenhouse gas emissions and reduce energy costs. Thus, the EU has set binding targets of at least **32.5 % increase in energy efficiency by 2030**, compared to a 'business as usual' scenario. Additionally, the new target for **re-**

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[3] Industrial Emissions Directive (IED, 2010/75/EU)

[4] The document comprises description of applied processes and minimum process requirements regarding energy efficiency measures (besides materials efficiency, emission levels for various substances, waste and noise), depending on new/existing plants and other limiting factors. Requirements comprise among others: process optimisation, regular maintenance, optimisation of the furnace design and melting technique, application of combustion control techniques, use of increasing level of cullet, use of waste heat boiler for energy recovery, use of batch and cullet preheating.

[5] Countries of the European Union, Norway, Iceland

[6] Following the 2015 Paris Climate Agreement, the European Union pledged to achieve greenhouse gas emission reductions of at least 40% by 2030 compared to 1990. With a view to this target and in order to pave the way towards energy transition the European Commission presented new, more ambitious rules in 2016, called the Clean Energy Package for all Europeans.

newable energy share on gross final energy consumption has been set to at least 32 % for 2030 (European Commission, 2018, last update 12/2020). In this regard, a revision and possible expansion of the EU-ETS is currently under discussion.

What is important for any energy saving project is the **application of monitoring and verification**, as this sets the basis of verifying the achieved savings. For those companies wishing to extend their knowledge basis and integrate energy management in their overall quality/environmental processes, the application of established management tools and processes in the Standard ISO 50001 can be an option.

In Europe, large enterprises either have to apply such energy (or environmental) management systems or regularly conduct energy audits every four years following the requirements of the **Energy Efficiency Directive** (Directive 2012/27/EU and its amendment in 2018).[7]

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[7] Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency (Text with EEA relevance.)

2.3 Overview of Energy Efficiency Measures

Reaching (theoretical) energy efficiency limits set by the rules of thermodynamics is not expected, but there are still limitations, especially due to ongoing practice and cost constraints. The more the "low hanging fruits" are harvested, the more difficult it gets to identify further feasible energy saving potentials. In the "energy maturity model" (cited in: (Fawkes et al., 2016) it is differentiated between:

- **(Good) housekeeping**: including maintenance, routine inspections, correct installation of all equipment, correct size of equipment according to actual demand, ensure proper insulation etc.
- **Use of control systems**: covering e. g. temperature control limits, reducing excess flows, using variable speed drives, using preventive maintenance
- **Simple modification**: change of equipment
- **Process integration**: using heat exchangers, closed-loop systems or waste heat recovery (WHR) and
- **Alternative processes**: such as combined heat and power plants, applying dynamic simulation and predictive controls, or applying new process technologies

The higher the energy maturity, the higher the potential savings, but the associated efforts, knowledge, complexity and business risks also increase. Thus, all energy saving projects should begin with easy and low energy maturity aspects. Improving single cross-cutting technologies such as motors, variable speed drives and their optimization are important for several industrial sectors, but these are not within the scope of this guideline. The same applies to the need of considering the impact of the status of industrial enterprises' buildings on the energy consumption. Process-related measures along the whole production process might be viable options for different industries and are explained in the industry-specific guidelines (Fawkes, 2016). These measures can include:

- The **optimization of steam systems** (minimize the number of heat transformations, preheating water or air, using energy efficient heat exchanger designs, minimizing/optimizing simultaneous heating and cooling)
- Optimization of **cooling and refrigeration**
- Recognizing the effects of **water chemistry** (mineral salts, dissolved gases etc.) on water quality/treatment requirements
- Installing **combined heat and power** instead of high-temperature heat losses
- Applying **heat recovery** both within one company or also to neighboring heat users or district heating systems
- Using **waste heat to power** for industrial processes with high waste heat temperatures
- Converting waste from production as an **energy source** (after screening options for re-use or recycling)

3

Overview of the Glass Fibre Sector

The following chapter provides an introduction to overall production processes in the glass fibre sector and their relevance to overall energy consumption as well as a statistical overview of production and energy consumption related figures in Europe.

3.1 Description of the Production Process and Process Steps

The European glass industry association (Glass Alliance Europe) is structured along five major sub-sectors[8] from which one of the smaller ones is related to glass fibre production (http://www.glassfibreeurope.eu/).

Glass fibre production comprises
- CFF, materials with high mechanical strength and low electrical conductivity, which are used e.g. in
  - Lightweight automotive applications (e.g. vehicle chassis, body, doors),
  - Compressed gas storage (e.g. hydrogen fuel tanks for electric vehicles),
  - Wind turbines (e.g. turbine blades), and
  - the aerospace industry (US. Department of Energy, Office of Energy Efficiency & Renewable Energy, 2017) as well as
- glass and rock wool for insulation in the construction industry and
- optical glass fibres for the telecommunications industry.

The latter application makes use of the typical characteristics of glass fibres such as a high degrees of purity, high-temperature resistance and very high thermal shock resistance.

It is worth noting that the categorization of glass-production sub-sectors is not fully consistent in different studies, especially glass and rock wool products are often categorized in different sectors. (Zier Michael, 2021)

Continuous filament glass fibre is produced and supplied in a variety of forms: roving, mat, chopped strand, textile (yarn), tissue, and milled fibre. The main end use (approximately 90 %) is the production of composite materials (glass-reinforced plastic, GRP), by reinforcement of both thermosetting and thermoplastics resins. (Scalet Bianca Maria, 2013)

Despite differences in production compositions and processing technologies of the different glass sub-sectors, the major process steps are the same for all of them and comprise:
- Batch preparation ,
- Melting and fining,
- Forming, and
- Finishing.

In the following, the main production stages relevant for all types of glass products are explained.

Batch preparation

Batch preparation has the purpose of mixing dry raw materials (silica and additives) appropriately and homogeniously to secure a glass melt of sufficient quality. Complications at this stage can lead to longer melting times and to problems with final product quality. Batch preparation includes crushing, sieving and storing of the repective components. In order to reduce dust and ensure homogeneity, the dry raw materials (and cullet, if applicable) are moistened with water (2-4% by weight). Electricity consumption that is necessary for the batch preparation is responsible for only a minor share of overall energy consumption. It is used for powering applicances such as bucket elevators, pneumatic conveyors and batch mixers. (Zier Michael, 2021)

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[8] Flat glass, container glass, tableware, glass fibres, others (incl. special glass)

Melting and Fining

Melting and fining is the core process of glass production and should lead to a thermally and chemically homogenous melt without crystalline or gaseous inclusions or other impurities. It takes place in a melting furnace/melting tank made of refractory materials at temperatures between 1200-1600°C. (Zier Michael, 2021)

Glass melting furnaces applied for glass fibres (apart for optical glass fibres) are designed as continuous tank furnaces. This means that the raw material is fed in at one end and the molten glass is taken out at the other.

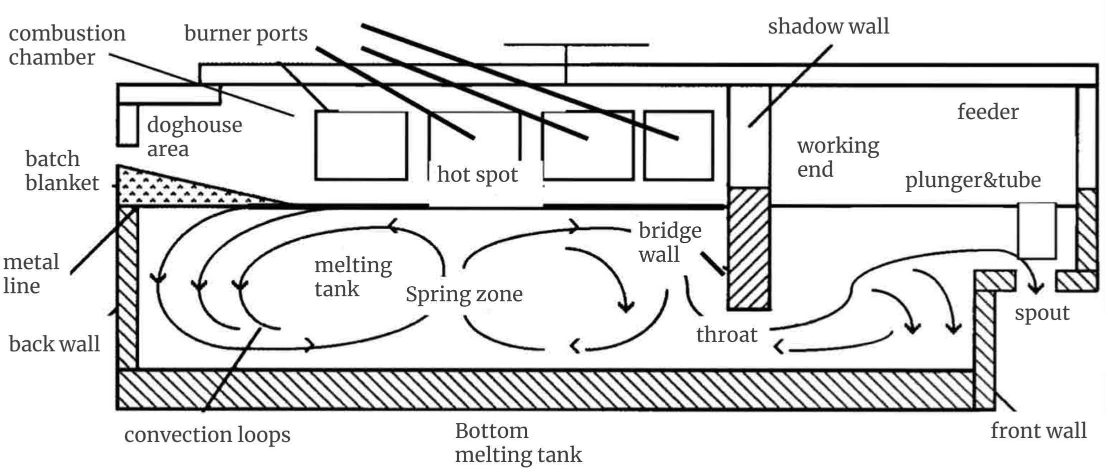
Typical characteristics of **continous furnaces** are:

- The tank (made of refractory material) is continuously charged with mixed batch throughout production campaigns of 5 to 15 years duration.
- The furnaces currently use fossil fuel (mostly natural gas, rarely also oil) firing with preheated air or oxygen.
- The different process steps take place in different sections of the furnace.
- The furnace melting capacity (glass pull) is usually expressed in the number of (metric) tons of glass melted per day (24 hours). Depending on the furnace and type of glass produced, the pull can vary from 20 tonnes per day to more than 700 tonnes per day (for glass production in general). (Hubert, 2015)
- The flame orientation can either be cross-heated or face-heated and
- Different types of flue gas heat recovery (recuperative or regenerative) are explained in more detail in the chapter 4 .

We differentiate between the **rough melting process** and the **fine melting process**. In the rough melting process, the introduced batch is decomposed at high temperatures. The resulting glass mass is very inhomogeneous and interspersed with gas bubbles. In the subsequent fine melting section, the molten glass is refined. This means that the molten glass is homogenised and freed from gas bubbles. The dwell time of the molten glass in the melting tank depends on the required glass quality. Finally, the glass mass is transferred to a separate area of the melting tank, where it cools down and reaches a viscosity suitable for shaping. (Leisin, 2019)

The following chart shows the main components of a glass furnace:

Figure 7: Components of Glass Furnace



Source: (Hubert, 2015)

For details on special furnace types please refer to the respective sections of chapter 4.

Forming and Finishing

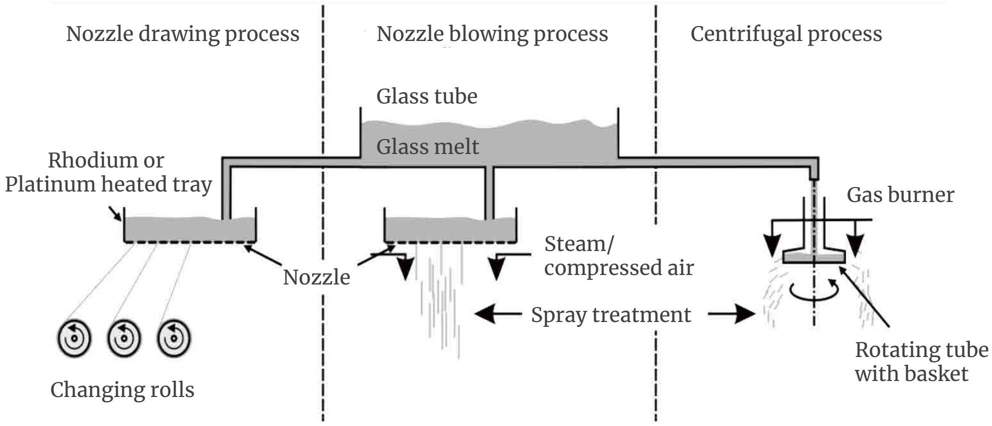
After passing through the melting furnace, the melted glass is shaped. In the case of glass fibres, three types of processes exist:

Nozzle drawing process: This process is used for continuous fibres that are used in reinforcing printed circuit boards and plastics or as an additive for textile fabrics. In the process, the molten glass is fed from the glass tank into a tank made of platinum and rhodium. There are nozzles at the bottom of the tub from which the glass runs out. To ensure constant temperatures, electricity is passed through the tub to heat the molten glass. The emerging glass filaments are wound onto rollers. The thickness of the filaments can be determined by the rotation speed of the rollers. It is between 5 and 20 µm, which is about as thick as the filament in a light bulb. In some cases, the threads are spun into a strand before being wound up. (EnArgus, 2021)

Nozzle blowing process: In this process, shorter glass fibres are produced. They are used as insulating fibres. As in the nozzle drawing process, the molten glass is passed through nozzles of a tub made of platinum and rhodium. Under the trough, the filaments are further defibrated by a jet of air or steam and driven to length. They are then sprayed with phenolic resin. The fibres pass onto a conveyor belt and are dried in a drying oven. They are then cut into pieces and pressed into sheets. (EnArgus, 2021)

Centrifugal process: The process is used to produce glass wool. For production, molten glass is passed through a rotating tube. At the end of the tube is a basket with holes. The rotation forces the glass through the holes. Concentrically arranged burners break up the glass fibres. The fibres are then treated as in the jet-blowing process. (EnArgus, 2021)

Figure 8: Forming Methods for Glass Fibres



Source: (EnArgus, 2021)

The step of finishing refers to the application of surface treatments and coatings, so called "sizing". The specific treatment depends on the type of product and is not further discussed in this guideline.

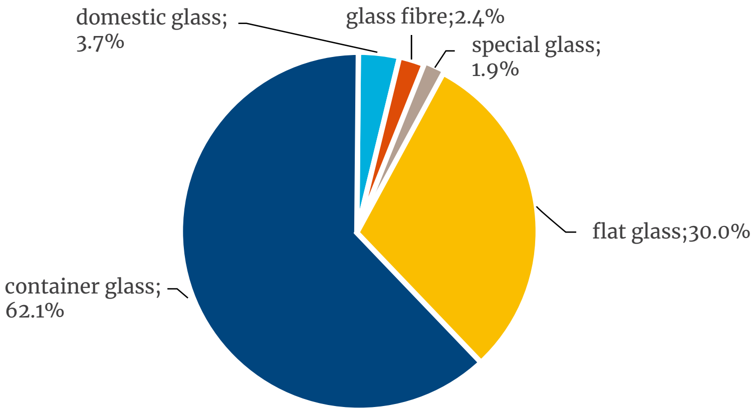
3.2 Current Situation and Development of Energy Efficiency in the Sector

This chapter further explains the current situation of energy consumption and energy efficiency of the glass (fibre) sector in Europe and provides an overview of the major energy-consuming processes relevant for this sector.

3.2.1 Energy Statistics and Benchmarks Glass (Fibre) Sector

Overall glass production in Europe totals to 36 million tonnes and comprises different sub-sectors/products, the largest being container glass and flat glass. Glass fibre production holds a smaller share: appr. 0.8 million tonnes, equivalent to 2.4% of overall glass production.

Figure 9: Production Shares (%) of Glass Production Sub-Sectors in Europe



Source: (WKO, Fachverband der Glasindustrie Österreich, 2019)

Below table provides an overview of glass production in European countries, which adds up to a total production output of approximately 36 Mt/year.

Table 1 Glass Production in Europe in Tonnes (EU 28, excluding insulation glass fibres, 2020)

GLASS TYPES	CONTAINER GLASS	FLAT GLASS [Unworked]	DOMESTIC GLASSWARE	CONTINUOUS REINFORCEMENT FIBRES	SPECIAL GLASS	OTHER	TOTAL
PRODUCTION	22331000	10773000	1132000	853000	542000	220000	35851000
Apparent Consumption	22477968	10374663	1151670	1238412	532899	539359	36314971
EXPORTS Extra-EU	1186884	882961	307251	188785	19781	594684	3180346
IMPORTS Extra-EU	1333852	484624	326921	574197	10680	914043	3644317
Exports/Imports	0.9	1.8	0.9	0.3	1.85	0.65	0.87
Imports Penetration	5.9	4.5	28.9	67.3	19.7	415	10.2

Source: (Glass Alliance Europe, 2021)

The following table shows the number of continuous filament installations and furnaces in the EU member states as of 2005[9]. Production volumes range from less than 50 tonnes per day (11), to medium sizes (50-100 tonnes per day), and to large furnaces with more than 100 tonnes per day.

Table 2: Continuous Glass Fibre Installations and Furnaces in the European Union in 2005

Member State	Number of installations	Number of furnaces (in operation in 2005)
Germany	3	5
Belgium	2	5
Czech Republic	2	4
France	2	4
Italy	2	3
Finland	1	3
Slovakia	1	3
The Netherlands	1	2
United Kingdom	1	2
Spain	1	2
Latvia	1	1
Total	17	34

Source: (Scalet Bianca Maria, 2013)

Unit energy consumption is defined as the energy input necessary for the production of one unit of output. In the case of glass production, this figure relates to "one tonne of glass produced". Following the discussions in scientific literature, it has to be underlined that the term "one tonne of glass" is not used uniformly – it refers to either one tonne melted or one tonne packed. Due to broken glass or glass not suitable for sale, the figures can deviate considerably. Waste fibre and drain glass can amount to 10-30% of process inputs (60250 kg of fibre glass waste and 1-13 kg of binder wastes per tonne of glass fibre product). (Scalet Bianca Maria, 2013)

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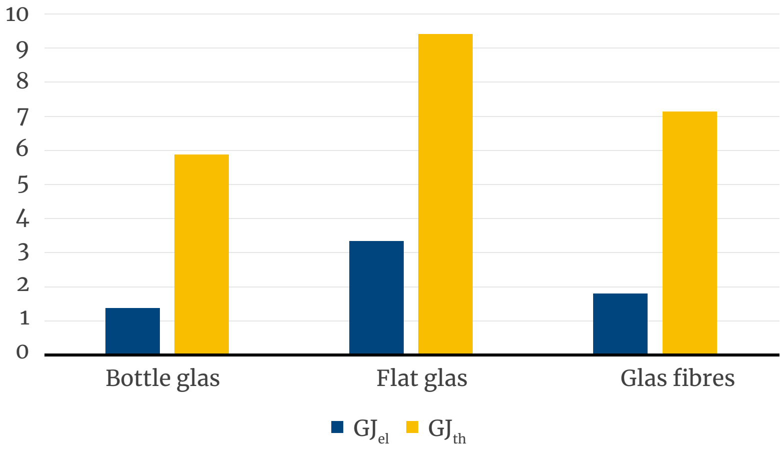
[9] Despite the relatively old source, the overall production sites seem to have remained in the same order as the current number of allocations also refers to 17 installations (the term 'installation' refers to a technical unit which performs one or more activities listed in Annex I of the EU ETS directive)

The following diagram shows the average unit energy consumption of different glass types which is in the range of 7.2-12.6 GJ/tonne (2.0-3.5 MWh/tonne). The major share of energy consumption (in the range of appr. 80%) is attributable to thermal energy.

Figure 10: Unit Energy Consumption (GJ/tonne) of Different Glass Types, (Leisin, 2019)



Each attempt to reduce overall (final) energy consumption ultimately targets the broader goal of **GHG emission reductions**. This can be achieved via various ways, including efficiency measures reducing final energy consumption, fuel switch and further initiatives as described in the following chapters of this guideline.

The table below shows current levels of different product benchmarks for glass products in the EU ETS (European Commission, 2021), given in tonnes of CO2 per tonne of product. Additionally, the table presents the average emission values for the top 10 % of most efficient installations. By comparing the most efficient installations and benchmark values, it can be seen that there is further room for reducing CO2 emissions, with considerable differences between the installations.

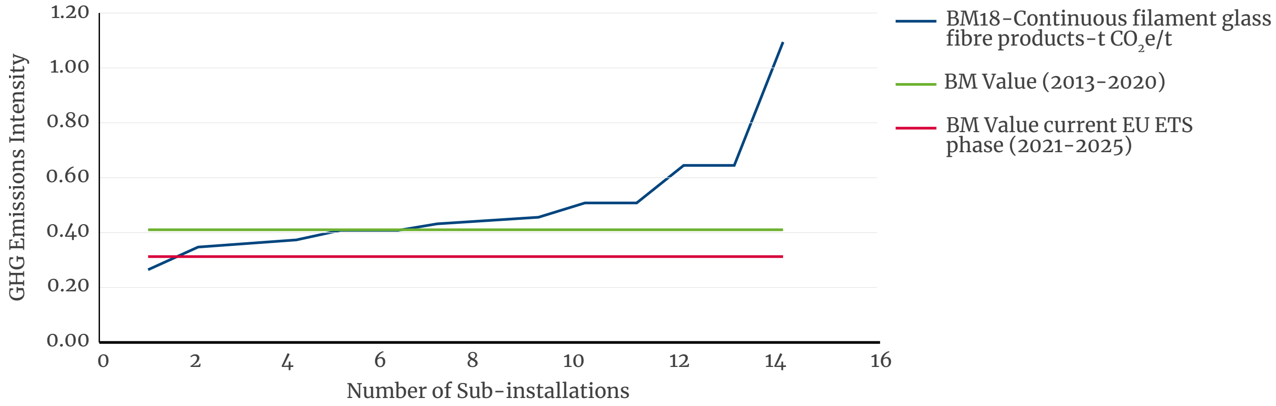
Table 3: Product Benchmarks

Product Benchmark	Average Value of the 10% Most Efficient Installations in 2016 and 2017 (t CO_2 Equivalents/t)	Benchmark Value (Allowances/t) for 2021 - 2025
Float Glass	0.421	0.399
Bottles and Jars of Colourless Glass	0.323	0.290
Bottles and Jars of Coloured Glass	0.265	0.237
Continuous Filament Glass Fibre Products	0.290	0.309

Source: (European Commission, 2021)

The following graph shows the GHG emission intensity for CFF production sites in Europe:

Figure 11: Statistical Data on GHG Emission Intensity of Continuous Filament Glass Fibres in Europe



Source: (European Commission, 2021)

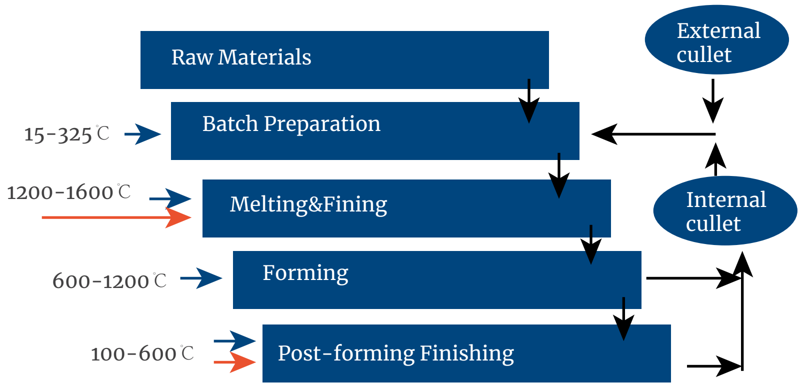
The blue line shows the actual GHG emission intensity of European continuous filament glass fibres producers, the red line shows the Benchmark (BM) value for the current EU ETS phase 2021-2025. Average GHG emission intensity of all installations amounted to 0.492t CO2e/t in 2016/2017, while the average GHG emissions intensity of the 10 most efficient installations was only 0.290 t CO2e/t. This means that the "average" producers still have room for improvement (or the need to buy emission certificates).

Another fact worth mentioning in the context of GHG is the considerable share of process emissions. Depending on the specific minerals and local geology, around 15-25%[10] of the overall CO2 emissions are process-emissions. These are emissions, which are not related to fuel-input, but inherent to the breakdown of carbonates in the raw materials such as limestone, dolomite or magnesite. These emissions are a natural by-product of the firing process and cannot be avoided (without changing the inputs). (Glass Alliance Europe, 2021)

3.2.2 Energy and Material Flows

The following chart provides an overview of the major energy and material flows. External cullet means cullet from other industries, internal cullet refers to broken glass from the process itself. The arrows depict the energy input and the approximate temperature levels (red arrow: thermal energy, blue arrow: electricity).

Figure 12: Production Steps for Glass Manufacturing



Source: adapted from (Zier Michael, 2021)

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[10] depending on several parameters of production, especially on the rate of cullet use

3.2.3 Energy Intensive Processes

To determine specific energy saving potentials and measures, one of the first steps is to identify major energy consuming processes.

Different sources provide different average unit consumption figures for glass fibre production. It can be assumed that these differences are due to the following facts:

- Different ways of grouping glass fibre (with/without insulation materials),
- Different definition of "one tonne of glass" (melted or ready to sale), and
- Different fuels used; rate of cullet used etc.

Nevertheless, the following figures can be taken as a rough indication of unit energy consumption and shares of sub-processes. They also underline the **dominance of thermal energy consumption over electricity consumption and the focus on the melting and fining process step** with a share of **around 80% of overall energy consumption**[11]. In Europe, the major fuel used is natural gas (97% of overall thermal energy).

Table 4: Unit Energy Consumption and Shares of Energy Consumption per Sub-Process of Glass Manufacturing

	Electrical Energy	Thermal Energy	GJ/t_{glass}	kWh/t_{glass}	Share (%)
Batch Preparation	y	n	0.195	54	3%
Melting & Fining	y	y	5.4	1,500	81%
Forming	y	n	0.26	72	4%
Post Forming-Finishing	y	y	0.845	235	13%
total	---	---	6.7	1,861	---

Source: (Zier Michael, 2021)

As shown in the above table, the major energy consumption share can be attributed to the furnace. Specific shares vary depending on the type of product and the specific production steps (see previous chapter). For glass fibres, post treatment and finish such as glass fibre drying and textile processing can also lead to considerable energy consumption, depending on the specific products.

For all glass types, however, melting and fining steps are the largest consumers of heat energy supplied from fuel (mainly gas), whereas electrical energy is relevant for all sub-steps (however to a considerably lower extent).

Major points affecting specific energy consumption according to the BAT document comprise:

- Capacity of the furnace: larger furnaces are more energy efficient due to the lower surface area to volume ratio.
- Furnace throughput: most furnaces achieve the most energy efficient production at peak load.
- Age of a furnace: the older the furnace the higher the specific energy consumption (up to 20 % higher than at the beginning of the campaign).
- Use of an electric boost (see chapter 4.5).
- (Increased) use of cullet (see chapter 4.2).
- Oxy-fuel firing (see chapters 4.3 and 4.4.) (Scalet Bianca Maria, 2013)

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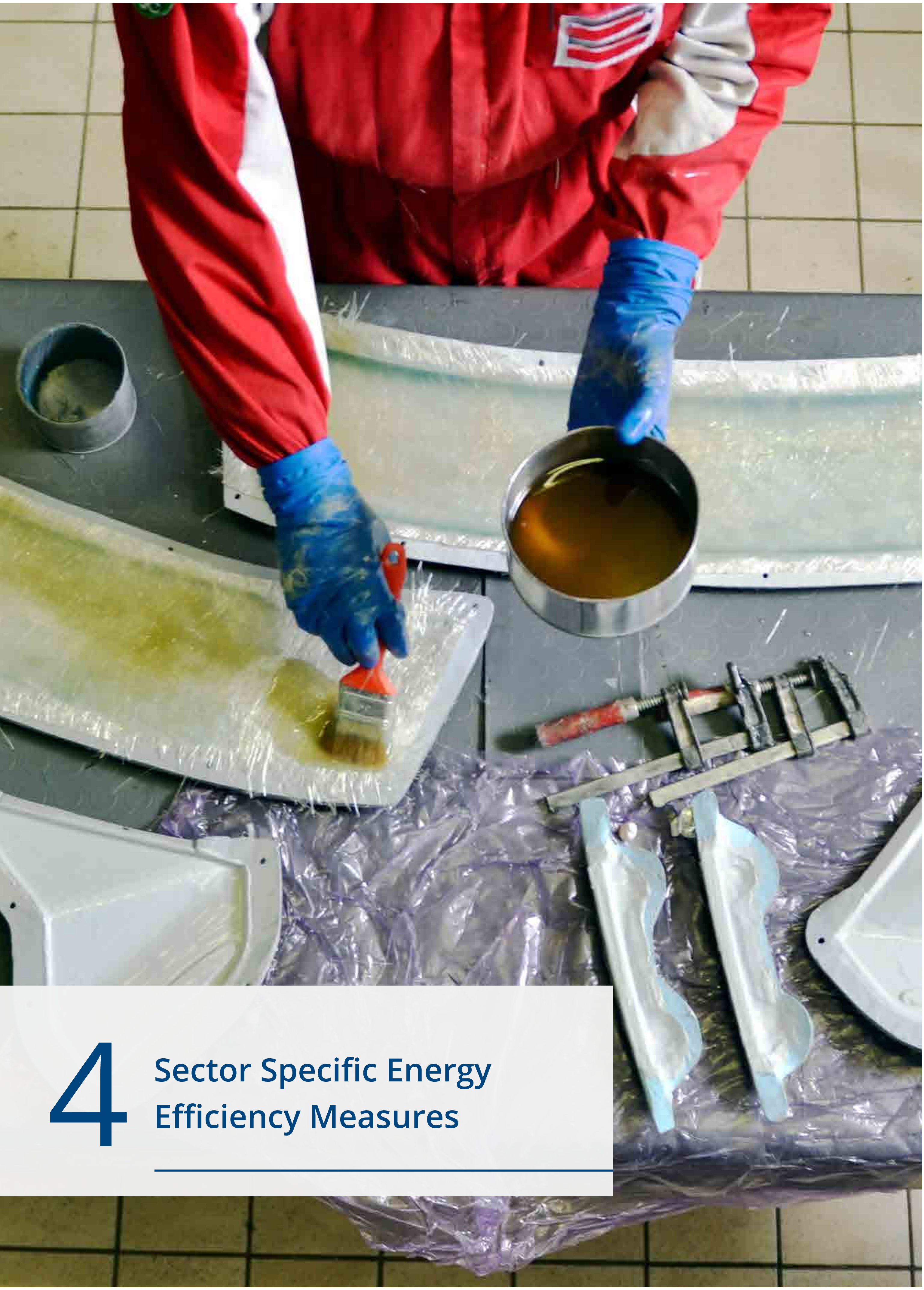
[11] For better comparability of data, thermal energy figures are shown in kWh and GJ.



4

Sector Specific Energy Efficiency Measures

Table 5 presents the energy efficiency measures presented in this chapter. Each chapter explains the baseline situation, the measure and its potential in terms of energy saving and greenhouse gas emission reduction. Due to the major share of energy consumption for melting and refining for all types of glass products, focus was put on this sub-step.

Table 5: Glass Fibre Sector Energy Efficiency Measures

Chapter	Measure	Process
4.1	Optimized Fluxing Agents	Batch Preparation
4.2	Glass (Fibre) Recycling	Batch Preparation
4.3	Oxy-Fuel - TCR Process	Melting and Refining
4.4	Oxy-Fuel Furnaces Regenerative (Eco-HeatOx)	Melting and Refining
4.5	Electric Melting, Electric Boosting	Melting and Refining
4.6	Batch and Cullet Preheating	Melting and Refining
4.7	Low Carbon Fuels (H_2, O_2)	Melting and Refining
4.8	Model Based Predictive Control (MBPC)	Conditioning and Forming
4.9	Pressure Drop Minimization	Sizing and Finishing

4.1 Optimized Fluxing Agents

4.1.1 Description of Baseline Situation and Energy Consumption

Fluxing agents are added to the raw materials mixture in order to reduce the melting temperature of the batch. Mainly alkali oxides such as soda ash (Na2CO3) or potassium oxide (K2O) are used for this purpose. In Germany, the most widely used fluxing agent in glass production is soda ash, which reacts to sodium dioxide (SO2) in the glass manufacturing process. Soda ash is a rare material and therefore often produced synthetically by the Solvay process. Soda ash accounts for only appr. 13% of weight of the total raw material but it adds to 70% of raw material cost. (Zier Michael, 2021)

4.1.2 Suggested Measures of Improvement

The proposed measure is to replace Soda ash by other fluxing agents, namely lithium compounds, which have been in use for only the last 5-10 years.

Lithium compounds are reported to have lower melting temperatures and corresponding lower thermal energy requirements compared to soda ash. Due to its chemical properties (small ionic radius and high ionic potential), lithium lowers viscosity and thermal expansion, resulting in better melting efficiencies and/or larger effective furnace capacities. (Institute for Industrial Productivity, 2021)

4.1.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Considering an average energy saving in the furnace of 8%, this would lead to energy reduction of 120 kWh per tonne of glass melted.

Table 6: Key facts of measure – Optimized Fluxing Agents

Key Facts of Measure – Optimized Fluxing Agents	
Investment Cost:	n.a. (cost difference of soda ash and lithium compounds)
Energy Savings: (thermal)	5-10% reduction of energy consumption in furnace: 120 kWh/t_{glass}
CO_2 Mitigation:	24 kgCO_2/t_{glass}
Advantage:	● Lower melting temperature, lower energy requirement ● Improved forming properties and better glass quality ● Cost advantage in comparison to soda ash
Disadvantage:	● -

4.2 Glass (Fibre) Recycling

4.2.1 Description of Baseline Situation and Energy Consumption

Generally speaking, there is a wide variety of glass products with different material properties and correspondingly different input materials. As shown in the table below, product compositions for glass fibres differ considerably from other product segments such as container glass and flat glass:

Table 7: Raw Materials for Glass Production in Germany

	SiO2[wt%]	Na2O[wt%]	CaO[wt%]	MgO[wt%]	Al2O3[wt%]	K2O[wt%]
Container glass	71-73	12-14	8.5-12	0-3.5	1-3	0-1.5
Flat glass	70-73	13.5-14	8.5-9	0-5	0.3-1.5	0.3-1.7
Glas fibers	52-65	<17	16-25	0-5	12-16	<2

Source: (Zier Michael, 2021)

Apart from raw material, internal and external cullet is added to the glass mixture (Figure 12). **Internal cullet** refers to glass that failed quality tests and could not be used for sale due to cracking, defects or other quality issues. Thus, internal cullet has about the same characteristics as the final product. **External cullet** is collected from post-consumer glass or other industries. Most glass sectors routinely recycle all internal cullet. Container and glass-wool industries use both internal and external cullet. For the glass fibre sector, use of internal cullet is limited “due to quality restraints” and external cullet use was restricted to some applications in the mineral wool sector in the most recent BAT document dated 2013. (Scalet Bianca Maria, 2013). Meanwhile, different applications exist. These are outlined below.

Glass fibre end-of-life-waste (especially compound materials) of consumer/industrial products is often landfilled for decomposing. This provides considerable optimisation potential for sustainable reuse and recycling. In Germany, e.g., glass fibre compounds (dashboards, bumpers from automobiles) are mostly shredded and thermally used. For old rotor blades from wind turbines a suitable disposal system has been established for combined energy (resin) and material (glass) recovery in cement plants – resin is used for energy purposes, glass as material input. In the rotary kiln, the silicon dioxide is completely integrated into the cement clinker and thus into a new product. However, the utilisable share of glass fibre waste is limited and only possible if other silica sources are substituted. (LAGA, 2019)

4.2.2 Suggested Measures of Improvement

Recycling of glass (either broken or final product after use comprises:

- (Increased) use of cullet in the production process (either internal or external cullet), and
- Recycling of end-of-life glass fibre for other purposes.

Both measures increase material efficiency by reducing the raw material input and the unit energy consumption. The first measure directly influences the energy consumption of glass fibre production, whereas the second does not directly relate to the glass fibre production process, but rather to an overall resource efficiency improvement. However, both aspects are considered important in terms of the overall decarbonisation pathway.

Cullet has a lower melting energy required than the raw materials. This is due to the fact that the chemical reactions required in the glass production process have already been completed and the mass is lower than the equivalent input materials.

A higher cullet share also leads to other benefits such as lower particulate emissions, and a higher furnace output. Furthermore, cullet is easier to preheat than (raw material) batch and the output of the furnace can be increased. On the other hand, especially when using external cullet, there is always the risk of impurities which could seriously affect the refractory and reduce the furnace live; additionally, the control of the composition and the physical characteristics of the output is reduced and can lead to quality issues.

Detailed data on the application of recycling in the glass industry focus on other, larger sub-sectors. E. g., the external cullet use in container glass production in Europe varies from less than 20% to more than 90%. Internal cullet is also used in the glass wool industry.

Glass fibre recycling is ongoing research and becoming a more attractive solution to reduce material losses as depicted in the following case studies. Due to above-mentioned disadvantages of using external cullet, most applications are limited to the use of internal cullet in the glass fibre industry.

Case Study: Glass Fibre Recycling at Electric Glass Fibre NL, B.V
The company Electric Glass Fibre NL, B.V operates its own recycling station for internal recycling and currently uses 6-8% of recycled materials in the production.
The company's aim is to recycle all their process waste glass fibres to avoid production losses. (R. Krijgsman, 2019)

Case Study: Use of Recycled Glass Fibre at Lanxess
In Antwerp, the company Lanxess uses waste from glass fibre production from post-industrial recycling. For three different types of glass-fibre reinforced polyamid-6-mixtures they apply recycled fibre at 30, 35 and 60% by weight. This material is especially suitable for frontends, pedal bearing brackets or battery carriers used in electric vehicles. (Königsreuther, 2020)

Case Study: Use of Recycled LCD glass for E-Glass and Glass Wool
Ongoing research also examines the applicability of recycling of specific glass types. E.g., LCD glasses are of high purity to ensure high display quality, and hence qualify for use in recycling. Researchers analysed the use of LCD glasses for E-glass and glass wool by measuring viscosity and liquidus temperature. It was concluded that for E-glass[12] replacement of original glass by LCD cullet would be possible at up to 25% by weight, for glass wool at 20% by weight. Since 2010, LCD glass cullet has been used in some E-glass production plants in Korea (Kim K.-D. H.-H., 2011)

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[12] E-glass is one of the most common glass fibre types, which is alumino-borosilicate glass with less than 1% w/w alkali oxides, mainly used for glass-reinforced plastics. (Wikipedia)

4.2.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Use of recycled material in general not only reduces the specific energy consumption of the production process, but also increases material efficiency (i.e., reduced raw material input per given unit of output) and additionally leads to positive side effects such as reduced waste disposal costs or efforts.

Roughly, it can be assumed that every 10% increase in the recycled glass share results in a 2.5-3% reduction in furnace energy consumption. (Scalet Bianca Maria, 2013). Applying the values from Table 4, which assume an overall energy consumption of about 1500 kWh/tglass, this would mean a reduction of 45 kWh/t for a 10% increase of cullet use.

Table 8: Key Facts of Measure – Glass Fibre Recycling

Key Facts of Measure – Glass (Fibre) Recycling	
Investment Cost:	Cost depending on the cullet used
Energy Savings: (thermal)	2.5-3% saving of furnace energy for each additional 10% of cullet used; 45 kWh/t_{glass}
CO_2 mitigation:	9 kg CO_2/ t_{glass} for each additional 10% of cullet used
Advantage:	• Lower energy consumption, increased resource efficiency • Lower particulate emissions • Furnace easier to preheat • Increase of furnace output
Disadvantage:	• Potential problems in the furnace due to impurities • Potential quality issues depending on the quality and composition of the cullet

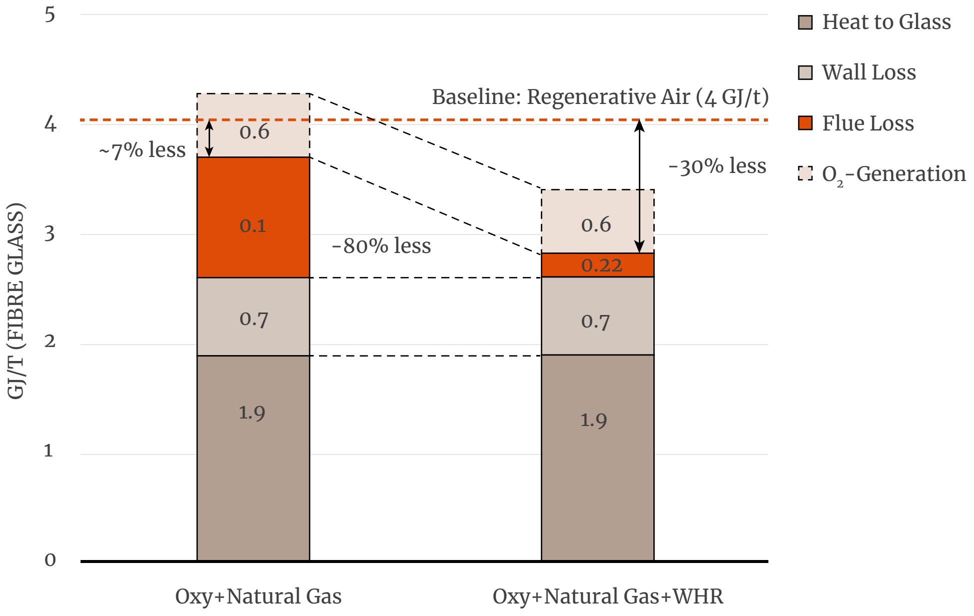
4.3 Oxy-Fuel - Thermo-Catalytic Reforming (TCR process)

4.3.1 Description of Baseline Situation and Energy Consumption

Oxy-fuel glass melting technologies were initially developed for large glass melting furnaces of all types with the aim to reduce combustion-generated NOx emissions (by up to 70 - 90%[13]) compared to regenerative air-fuel furnaces. A second key incentive for oxy-fuel melting, compared to regenerative air-fuel combustion, is a significantly higher fuel efficiency, without the expense of regenerators or other **heat recovery systems**. Compared to air-fuel furnaces even with highly efficient regenerators (total energy consumption baseline at ~ 4 GJ/t), a conversion to an oxy-fuel furnace can result in a 7.5% reduction in specific fuel consumption. About 25% (~ 0.92 GJ/t) of the fuel energy input is still lost as sensible heat in the flue gas. This happens due to imbalances in heat capacity ratios in the flue gas and purified oxygen streams, since established **waste heat recovery technologies** today are not utilized in oxy-fuel melting furnaces. (Figure 13, red area).

Thus, including the primary fuel requirements for the production of oxy-fuel – which depends on the share of renewables in the energy mix (Figure 13, blue area) – overall energy consumption of oxy-fuel furnaces could lead to an overall consumption of 4.3 GJ/t, which is higher than the baseline energy consumption of regenerative air-fuel furnaces. (Chakravarti, Alexander, & Kobayashi, 2021)

Figure 13: Comparison of Specific Fuel consumption at Oxy-Fuel with/without Heat Recovery (HR) Furnaces to Regenerative Air-Fuel furnaces (4.0 GJ/t) for a 300 t/d Furnace with 50 % Cullet



Source: adapted from: (Chakravarti, Alexander, & Kobayashi, 2021)

In order to recover the substantial amounts of waste heat produced by oxy-fuel processes (while still taking advantage of the benefits of oxy-fuel glass melting such as the substantial reduction in NOx emissions), **thermo-chemical heat recovery (TCR)** and its variations are promising options to increase overall fuel efficiency reduce at the same time CO2 emissions.

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[13] Baseline for NOx Emissions for air-fuel furnaces: ~ 4.7 – 5 kg/MT compared to 0.4 kg/MT after conversion to oxy-fuel (Source: Oxy-fuel glass melting trends in Asia, https://www.airproducts.co.uk/-/media/airproducts/files/en/337/337-17-001-us-oxy-fuel-glass-melting-trends-in-asia.pdf)

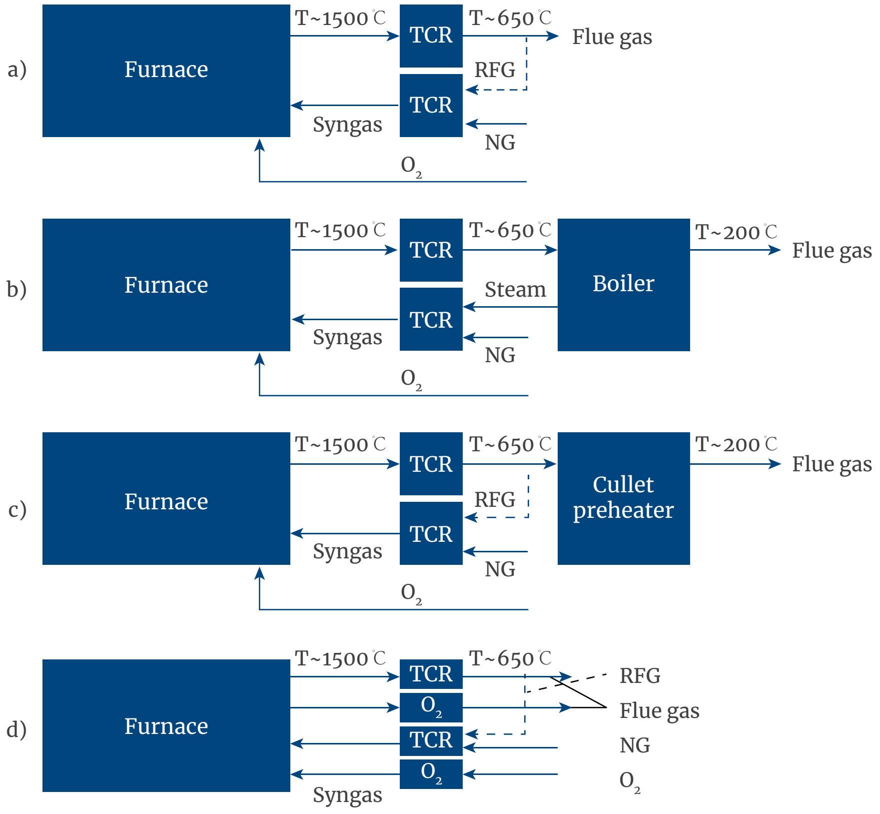
4.3.2 Suggested Measures of Improvement

The **TCR process is a heat recovery technology** based on endothermic chemical reactions at high temperatures. It is exclusively used in oxy-fuel fired glass furnaces. A principal concept of the underlying process is illustrated in Figure 14, section a.

The process circle begins at one of the regenerator checkers (TCR blocks) - which are utilized and preheated (~1.250 °C) in a similar way as conventional alternating regenerators for HR in air-fuel furnaces. In this reforming checker (i) **natural gas** (NG; manly CH_4) is mixed with recirculated (ii) **hot flue gas** (RFG; mainly H_2O and CO_2) to **steam reform** the gas mixture. At this specific stage, a hot “**syngas**” fuel that mainly consists of hydrogen (H_2) and carbon monoxide (CO) is generated, resulting in a significantly increased heating value of the mixture. The syngas, is than combusted **with oxygen** in the glass furnace, thus providing thermal energy for glass melting. In order to continuously maintain the endothermic process of steam reformations during the melting process, two reformers are needed. Therefore, regenerator checkers are utilized and operated in alternating modes: In the first mode, the regenerator is heated to the target temperature via the exhaust gases from the combustion chamber. In the other mode, the steam reformations cool down the process. When the regenerator is so cold that this steam reformation no longer takes place, it is switched and operates in the alternate mode. . (Kobayashi, et al., 2015)

The TCR process is only used for oxy-fuel furnaces, because only this type of furnace guarantees - due to the lack of nitrogen – high concentrations of H_2O and CO_2 (80–95%) in the flue gas. This is essential for an efficient reforming process, and respectively for endothermic reactions.
The TCR regenerators are similar in design to conventional air heating regenerators, but have only 33% of the size in the checker volume, making the retrofit or rebuild an economically attractive option.

Figure 14: Different Thermochemical Heat Recovery (TCR) Processes: (a) – Baseline; (b) TCR + Steam Boiler; (c) – TCR + Cullet Preheater; and (d) – TCR + O_2-Regenerator; RFG: Recycled Flue Gas.



Source: adapted from: (Zier Michael, 2021)

4.3.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

The positive effect of TCR installations on production and product quality, as well as reduced natural gas and oxygen consumption is well reported within a theoretical and experimental framework. It is highlighted that fuel savings with TCR are about 28% relative to the air regenerative and 20 % compared to an oxy-fuel furnace for a 300 t/d container melting unit. For units at lager scale, fuel savings are expected to be higher because the total wall losses are lower per unit glass pulled. Further, a combination of various heat integration and recovery options were investigated for the same furnaces. Combined regenerative heat recovery using TCR and O2 regenerators yield fuel savings of up to 11 % (Figure 14d). An installation of a cullet preheating unit combined with a TCR system leads to fuel savings of 29 % (Figure 14 c), whereas a waste heat boiler (Figure 14 b) could lead to fuel savings of 20 % compared to oxy-fuel baseline. (Kobayashi, et al., 2015)

Case Study - Commercial Installation: Mexico, 50 t/d container glass furnace:
A TCR system was first demonstrated on a 50 t/d container glass furnace in September 2014 and has been operating reliably since then. The technology stores waste heat from the hot oxy-fuel flue gas in regenerator beds and uses this energy to reform a mixture of natural gas and recirculated flue gas to hot syngas which is combusted with oxygen in the furnace. Operation of the TCR system in Mexico furnace resulted in 16 % to 18 % reduction in energy consumption compared to the baseline oxy-fuel furnace. (Gonzalez, et al., 2016)

Table 9: Key Facts of Measure – Oxy-Fuel - TCR

Key Facts of Measure – Oxy-Fuel - TCR	
Investment Cost:	Not known
Energy Savings: (thermal)	0.22 MWh_{th}/ t_{glass} (baseline oxy-fuel without HR)
CO_2 mitigation:	44 kg CO_2/ t_{glass}
Advantage:	● Non-catalytic reforming process ● Low NO_x Emission ● Scalable melting technologies
Disadvantage:	● High CAPEX for relatively small incremental heat recovery at O_2 recuperators

4.4 Oxy-Fuel Furnaces Regenerative (Eco-HeatOx)

4.4.1 Description of Baseline Situation and Energy Consumption

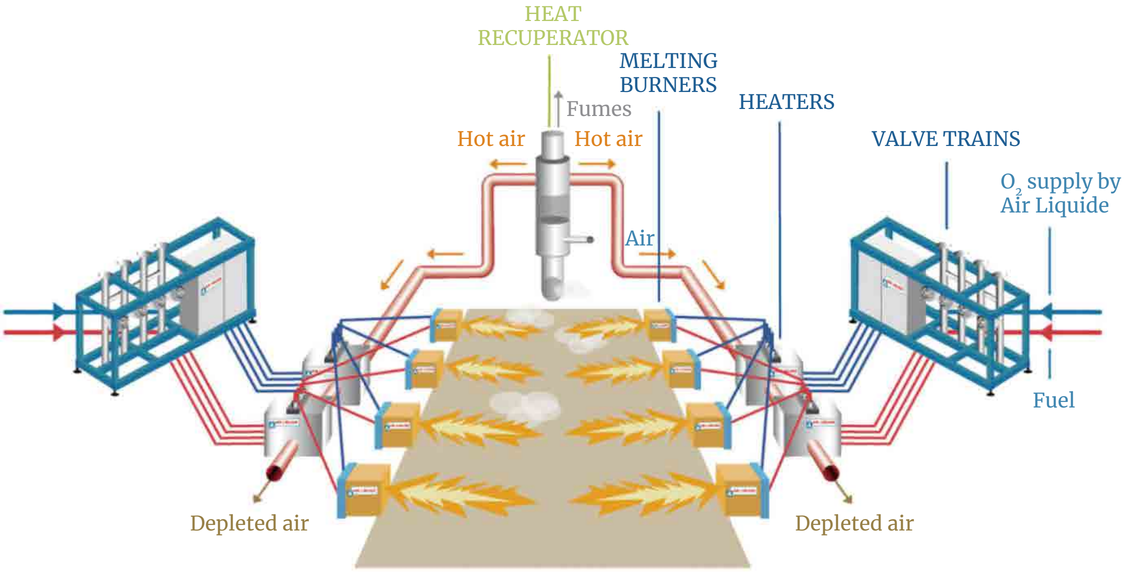
In the glass industries, oxy-fuel combustion has been widely used for fibreglass and technical glass production to improve the combustion process, reduce air pollutant emissions and save fuel. As mentioned in previous chapters, oxy-fuelled furnaces can result in a 7.5% reduction in fuel consumption (mainly natural gas) compared to air-fuel furnaces with highly efficient regenerators. Studies report that even without any additional energy recovery measures, the average energy saving potential of oxy-fuel furnaces is 25 – 35%[14] compared to recuperative furnaces. For large regenerative furnaces the energy saving potential amounts to up to 15%. (Kim, et al., 2016) However, oxygen can be provided and pre-treated with different supply systems to leverage the full potential of energy efficiency in the melting process.

4.4.2 Suggested Measures of Improvement

Air Liquide has developed a special method of oxy-fuel combustion technology, called **Eco-HeatOx**. This technology introduces heat recovery systems for small and medium-sized furnaces using natural gas and oxygen (in liquid form) through a heat-oxy combustion technology glass furnace. In this system, the overall consumption of fuels is reduced by **preheating** the reactants (natural gas and oxygen) up to 550°C with waste heat from furnaces. A principal concept of the process is illustrated in Figure 15.

The heat recovery system is composed of (i) a primary heat exchanger (recuperator), which allows heating air at ambient temperature up to ~ 700 °C by using hot flue gas (fumes) from the furnace; (ii) a sequential heat exchanger for the purpose of preheating the oxygen up to 550 °C and the NG up to 450 °C with gases form the primary heat exchanger; (iii) HeatOx proprietary burners which can operate with “cold” as well as with “hot” oxygen/natural gas mixture; and (iv) valve trains and automation equipment to control and measure the oxygen and natural gas flow rate of every burner. (Kim, et al., 2016)

Figure 15: Eco-HeatOx process for oxy-fuel furnaces



Source: (www.ecoheatox.com, 2021)

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[14] Including the energy consumption for oxygen production.

4.4.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

In Bulgaria, a glass factory uses a pilot Eco-Heat Oxy-fuel combustion. Following experimental data of this factory **Eco-HeatOx** technology is able to achieve about 19% efficiency gain **compared** to **regenerative air-fuel furnaces**. Precondition is that the targeted design temperature of the reactants of 450°C is reached. (Akviran, 2016)

Furthermore Table 10 presents the results of energy savings between **HeatOx** mode (preheated reactants) and **ColdOx** mode (without heat recovery). At pilot plant level, HeatOx could reduce CO2 emission by about 8 % of CO2 compared to a ColdOx combustion. (Caumont-Prim, Paubel, Juma, & Jarry, 2018) and (Kim, et al., 2016)

The economic feasibility of the technology is outlined for two case studies (float and a hollow glass furnace[15] in (Liquide, 2017). It is estimated that total savings due to reduced fuel consumption can be up to 300,000 EUR per year with a CAPEX of 1.66 million EUR for the hollow glass or up to 1.1 million EUR per year with a CAPEX of 4.25 million EUR for float glass. Today, about 35 furnaces (293 units) are operating with oxy-combustion in the EU (mainly fibre-glass and technical glass production). These plants could be converted to oxy-combustion with Heat ox / TCR. In principle (with conversion/replacement of the plants), all plants (i.e. 628 in Europe) could be converted (depending on economic results) “with any type of glass and every fuel type”. (Pasabahce Bulgaria, 2016)

Table 10: Key facts of measure – Oxy-Fuel Furnaces Regenerative (Eco-HeatOx)

Key Facts of Measure – Oxy-Fuel Furnaces Regenerative (Eco-HeatOx)	
Investment Cost:	~ 42 – 85 tEUR/ t_{glass} [16]
Energy Savings: (electricity)	13.8 kWh /t_{glass} (compared to baseline ColdOx) [17]
CO_2 mitigation:	23 kg CO_2/ t_{glass}
Advantage:	• Reduced energy costs • Flexible energy sourcing • Limited additional CAPEX with less than 3-year payback • Replicability and transferability potential
Disadvantage:	• Technology is still in a piloting stage

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[15] No detail data for manufacturing pull rate; calculation including Licensee Fee between 2.2 – 2.4 % of CAPEX

[16] Underlying pull rate of 50 – 100 tonne/d

[17] Electricity consumption for oxygen production is assumed to be in total 0.6 GJ/t or 166 kWh/t – 8 % efficiency gains are observed (Figure 15)

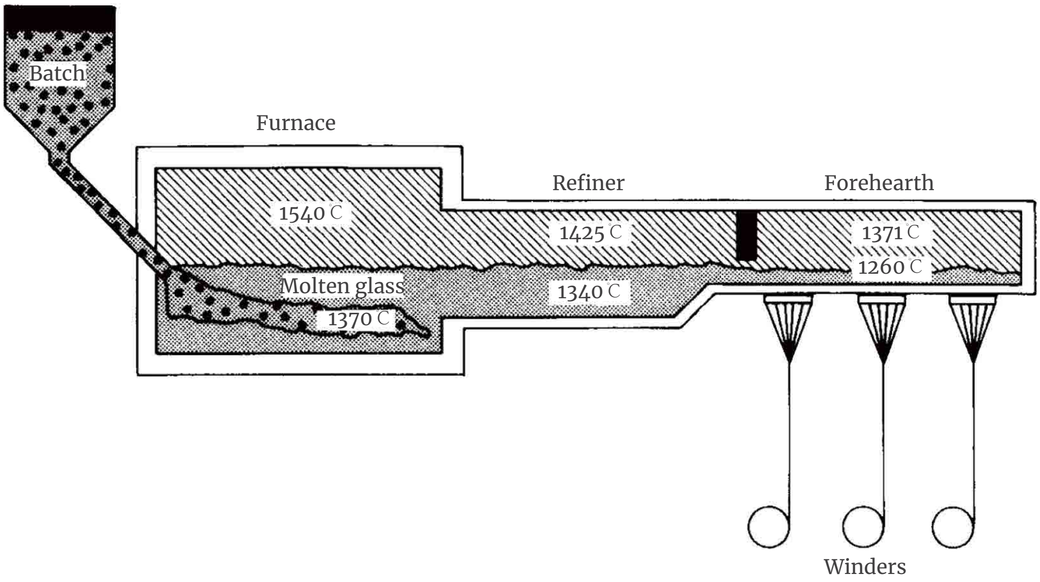
4.5 Electric Melting, Electric Boosting

4.5.1 Description of Baseline Situation and Energy Consumption

Glass melting is an energy-intensive process. The net melting energy needed to convert mixed raw material into fully melted and refined glass is about 0.6 kWh/kg. This assumes about 20% cullet, and varies to some extent according to both cullet percentage and glass type. The thermal efficiency of glass melting furnaces varies according to furnace design and glass type. Nevertheless, even the best fuel-fired furnaces reach thermal efficiencies of only around 45%, and many have thermal efficiencies of significantly less than this (Stormont, 2010).

As illustrated in Figure 16, the temperatures of the molten glass in the furnace are slightly below 1,400 °C. In order to cover the losses of the heat transfer to the glass, energy with higher temperatures must be supplied from combustion. In this process, energy is lost both via heat transfer from the furnace superstructure and via thermal energy in the residual waste gases, even if heat recovery systems such as regenerators or recuperators are used (Stormont, 2010).

Figure 16 Furnace for Glass Melting (Wallenberger, Watson, & Li, 2001)



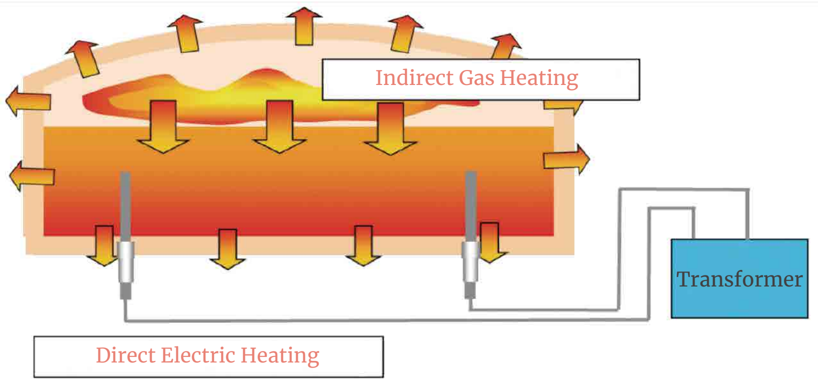
4.5.2 Suggested Measures of Improvement

The most effective method to eliminate or reduce energy losses caused by heat transfer is to implement immersed electrodes in the form of either electric boosting or all-electric melting.

With immersed electrodes in the glass connected to a suitable power supply and transformer, an electric current can be passed through the glass, releasing heat energy directly into the glass itself, with no significant losses in the process (Stormont, 2010).

Selection of the optimum number, positions, spacing, size, immersion and connection arrangements for boosting electrodes all contribute directly to the difference between an efficient and an inefficient boost system design (Stormont, 2010).

Figure 17: Electric Melting and Boosting (Stormont, 2010)



The temperatures in the furnace need to be analysed in order to implement a coordinated concept and adequate positioning of the electric boosting system (Stormont, 2010).

Electric boosting and melting technology maximize the efficiency of the process by the following points (Reynolds, 2018):

- Boosting heat energy can increase and homogenise the glass temperature (especially of low transmission types).
- Boosting in the hot spot will reinforce desirable convection currents (i.e., improve the ‘thermal barrier’ between the melting and refining zones).
- Boosting in the refining zone can help to reduce stagnant glass and control throat temperature.

A switch to fully electric melting using decarbonised electricity would eliminate CO2 emissions from glass melting which are generated from the combustion of fossil fuels. However, the implementation of this promising technology is still limited today by the size of the installations, the glass composition, and the quantity of cullet contained in the batches (Glass Alliance Europe, 2021).

Electric melting is available for small furnaces (< 200 tonnes/day), it still needs to be demonstrated for large furnaces used in flat or container glass production (from 200 to 1.000 tonnes/day). For certain glass compositions (e.g., e-glass for continuous filament glass fibres) there are technical aspects (associated with the electrical conductivity) which limit the heat input of electrical energy for melting (Glass Alliance Europe, 2021).

One precondition for all-electric glass melting is the stability of the grid and the safety of electricity supply since glass furnaces need permanent and stable energy feed and cannot operate intermittently. Additional factors influencing the usefulness of this technology are the cost of electricity, the quality of melting (especially with high levels of cullet) and the quality requirements of the final glass products (Glass Alliance Europe, 2021).

4.5.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

With today's best boosting technology, the boost system energy requirements amount to 0.48 kWh per kg, or 20 kilowatts of continuous power input per additional tonne per day (tpd) of glass. Savings of up to 17% of the overall energy consumption of the melting process are possible (Stormont, 2010).

It is expected that the investment costs will decrease over the following decades. Currently the capital expenditures are 130 €/t of glass production capacity (Szczeniak, Bauer, & Kober, 2020).

The overall GHG emissions reduction depends on the electricity mix on site.

- In the case of electrical melting, the entire thermal energy for melting and fining is replaced by electrical energy from the grid. For Europe, a CO2 reduction potential of approx. 30% is estimated. If the electricity is solely generated from renewables, the emissions can be reduced by 75-100%.
- For electrical boosting it can be assumed that 30% of the thermal energy used for melting and fining is saved and 20% of the thermal energy is replaced by electrical energy (Szczeniak, Bauer, & Kober, 2020).

The savings in the table below apply to electric boosting only. In the case of electric melting, all of the energy required for melting and fining would be covered by electricity. This would lead to considerably higher CO2-emissions given the existing electricity mix.

Table 11: Key Facts of Measure – Electric Boosting

Key Facts of Measure – Electric Boosting	
Investment Cost:	€1.3 million per site 13 €/ t_{glass}
Energy Savings: (thermal and electricity)	750 kWh_{th}/ t_{glass} -300 kWh_{el}/ t_{glass}
CO_2 mitigation:	-34 kg CO_2/ t_{glass}
Advantage:	● Glass quality improvement
Disadvantage:	● High analysis effort required before the system can be implemented

In terms of global emissions, it is better to burn fuel in the glass furnace than to use it to generate electricity for electric melting. In places where the CO2-emissions of electricity are high the measure "electric melting and boosting" should be combined with production of renewable energy on site (Stormont, 2010).

4.6 Batch and Cullet Preheating

4.6.1 Description of Baseline Situation and Energy Consumption

The entire thermal energy is transferred to the furnace. The batch and cullet are typically introduced into the melting furnace at ambient temperatures (Zier Michael, 2021).

4.6.2 Suggested Measures of Improvement

Batch and cullet preheating utilize exhaust gas waste heat to preheat the batch and cullet mixture. Normally batch and cullet are fed into the furnace without any additional heating input. This concept returns recovered energy directly back into the melting process and is consequently not susceptible to external factors. It can be applied at the existing glass production chain without interrupting the process. Batch and cullet are preheated to about 300 °C. This reduces fuel consumption and saves energy. Additionally, batch and cullet preheating reduces dusting problems and provides safe removal of humidity during batch preheating. (Dolianitis, et al., 2016).

Other benefits associated with the operation of a batch preheater include:

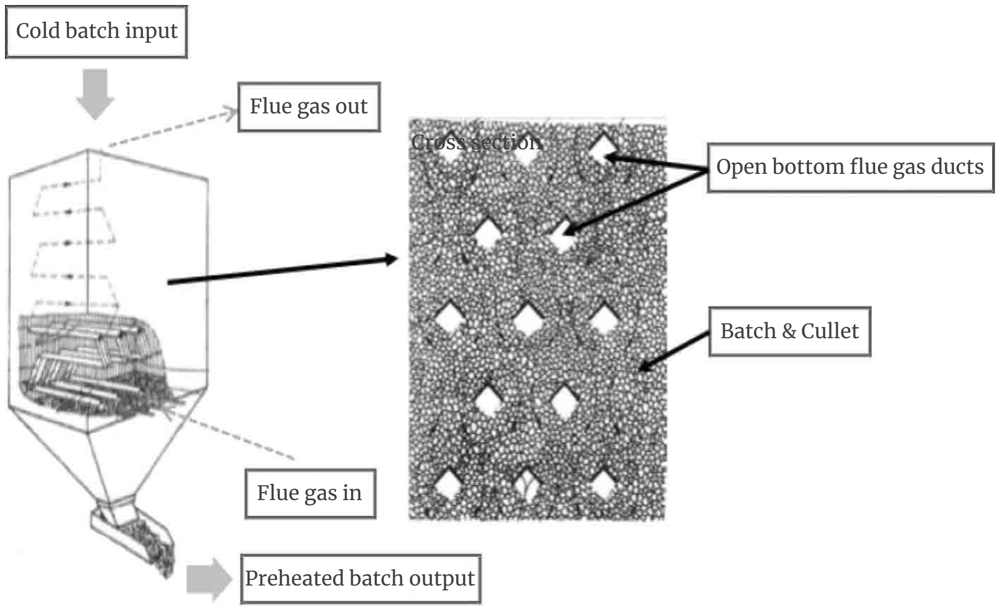
- The reduction of furnace wall temperatures,
- The removal of SO, HCl, and HF from the waste gases, since the batch acts as a scrubbing agent at direct contact systems,
- And the recovery of selenium during flint glass production (Beerkens, 2009).

The following limitations have to be considered before implementing “batch and cullet preheating” application (Dolianitis, et al., 2016):

- Large space requirements due to a large amount of exhaust gas is transported: the batch preheater should be close to the furnace doghouse to avoid dusting issues and heat losses from the transport system,
- Deterioration of the preheater structure due to corrosion and high temperatures,
- Odour issues in case of increased organic residues on the cullet.

There are several different types of batch and/or cullet preheating systems applied in the glass industry. The following figure demonstrates the basic concept of batch preheating. Basically, hot flue gas is sent through tubular heat exchangers which are positioned in the batch (Barklage-Hilgefort, 2009).

Figure 18: Basic Concept of the Batch Preheating System Nienburger type (Barklage-Hilgefort, 2009)



4.6.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Batch and cullet preheating is one of the best available techniques that leads to improved energy efficiency and reduced CO2 emissions. Over the past 30 years preheating systems have been installed in more than 10 different plants in Europe. On average, specific savings of 12-20% are achievable. In the meantime, problems such as the spread of dust and material clogging have been solved (Zippe, 2011).

Depending on the amount of preheated batch and cullet, energy savings are in the range of 10–20%. Furthermore, increased pull rates of 10% and payback periods in the range 3–4 years have been reported (Zier Michael, 2021). This results in a realistic saving of 15% based on the thermal energy consumption of the “Melting & Fining” process.

Table 12: Key facts of measure – Batch and Cullet Preheating

Key Facts of Measure – Batch and Cullet Preheating	
Investment Cost:	€2.2 million per site 22 €/ t_{glass}
Energy Savings: (thermal and electricity)	225 kWh_{th}/t_{glass}
CO_2 mitigation:	45 kg CO_2/ t_{glass}
Advantage:	• Approved, simple technology since 30 years • Removes SO, HCl, and HF from the waste gases
Disadvantage:	• Large space requirements • Preheater deterioration (due to corrosion and high temperatures)

4.7 Low Carbon Fuels

4.7.1 Description of Baseline Situation and Energy Consumption

In Europe, in glass production, the main fuel used for providing thermal energy is natural gas. The glass industry's energy demand and consumption has been discussed in detail in chapter 3.2.

4.7.2 Suggested Measures of Improvement

Options to reduce GHG emissions associated with burning fossil fuels include the switch to electric melting and boosting, as described in chapter 4.5, or the substitution of fossil fuels with alternative gaseous energy carriers: **biogas, solid biomass and its gasification products, synthetic methane and hydrogen.** Applications of these fuels are not yet available on industrial scale, but limited to demonstration projects. One of the major limitations is their non-(yet)-competitive price compared to natural gas. (Zier Michael, 2021)

Due to limited availability of biomass, and land use competition with food crops, the described measure concentrates on the use of hydrogen and synthetic methane. However, in principle (and already tested on semi-industrial scale) it is also possible to partly substitute natural gas by (untreated) **biogas in a co-firing approach.** Research in a glass melting furnace in Germany shows that a (partial) fuel switch does not considerably affect the combustion behaviour, product quality or refractory properties. Despite differences between natural gas and biogas in terms of gross calorific values[18], amongst others, substitution rates of up to 30% by energy input are possible without negative impacts on combustion or product quality. Currently, however, the main limiting factor is the availability of sufficient biogas in the vicinity of glass plants. For the time being, biogas is not economically viable due to low costs for natural gas. (Marcel Fiehl et al., 2017)

"Power-to-X" technologies (PtX) split water with the help of electrolysis and either use the hydrogen directly or process it into methane or liquid energy sources. The gaseous and liquid fuels produced with PtX technologies are called "power fuels". In case renewable electricity and non-fossil CO2 sources are used, power fuels can be considered climate-neutral and renewable energy sources. They can be used in gaseous and liquid form for both fuel purposes and as raw materials in the chemical industry. For high-temperature heat processes, with limited options of direct use of renewable energy, such as the glass melting process, those fuels are one powerful future technology on the way to decarbonisation.

The starting point for all conversion processes is the separation of water into hydrogen and oxygen in an **electrolysis process** (using renewable electricity). Both this process for the production of hydrogen and the production of synthetic methane through a subsequent methanation of the hydrogen is referred to as **Power-to-Gas.** (DENA, 2018) Both fuels could – in principle – be used for high temperature process heat applications such as the glass (fibre) industry.

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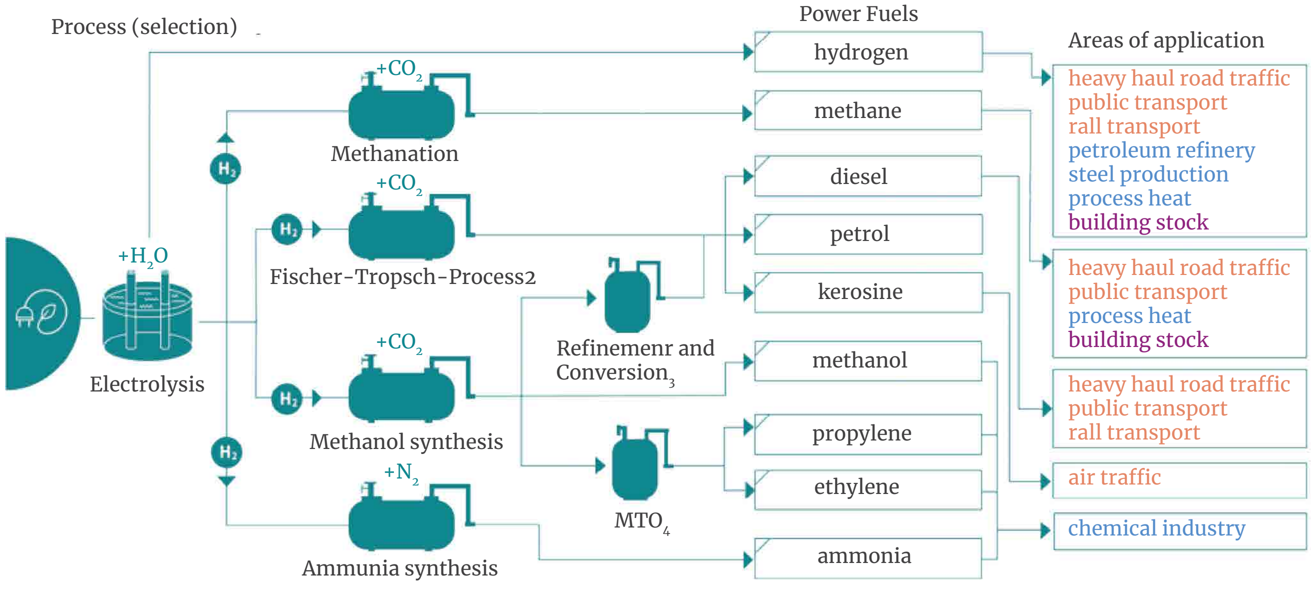
[18] Biogas from energy crops: 19.8-23.4 MJ/m³

The following chart illustrates different types of electrolysis and their possible applications.

Figure 19: Processes and Applications of Electrolysis



Source: translated from: (DENA, 2018)

In Germany, electrolysis has been available for several decades and its extensive use in the energy sector is on the threshold of the growth phase. Investment and operation costs are expected to decrease due to scaling up in terms of production quantity and size, standardisation of components and optimisation of plant concepts. Currently, there are more than **30 PtX pilot projects** with an electrolysis plant output of about 25 MW. Not only start-ups but also established companies are currently testing new processes, components and operating concepts. (DENA, 2017)

The following table summarizes the state-of the art of electrolysis and methanization processes. In the future, efficiency rates might increase by more than 10 percentage points (reaching up to 95% for SOEC electrolysis). Investment costs might decrease to less than one third of current prices (e. g., 250-400 €/kW for alkaline electrolysis).

Table 13: State-of-the Art and Development of Electrolysis and Methanization

	Electrolysis			Methanisation	
Type	Alkaline Electrolysis	PEM-Electrolysis	High Temperature Electrolysis (SOEC)	Catalytic Methanization	Biologic Methanization
TRL[19]	9	8	6	8	7
Advantages	Cost-effective (large plants), long term experience	Compact plants, better dynamics, good scalability, no corrosion	More efficient and cost-effective when using waste heat	Good scalability, high quality waste heat	Robust, flexible, quick reaction time
Challenges	Lye, cold start and partial load behaviour	Expensive material, Material requirements	Process at high temperature	Expensive material, low flexibility; Purity of the used gases	Biological system, up to now, to multi-MW plant
Efficiency	62-82%	65-82%	65-85%	77-83%	77-80%
Investment	800-1500€/kW	900-1850 €/kW	2200-6500 €/kW	400-1230€/kW	400-1980€/kW

Source: adapted from: (DENA, 2017)

4.7.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Using PtX-based fuels leads to a GHG emission reduction rather than to (final) energy savings. The extent of GHG reduction depends on the substitution rate of fossil fuels, and the CO2 emissions linked to the production of alternative fuels. The following table assumes that PtX-fuels are solely produced from renewable sources.

Table 14: Key Facts of Measure – Low Carbon Fuels

Key Facts of Measure – Low Carbon Fuels (Hydrogen and Synthetic Methane)	
Investment Cost:	800-1500 € per kW electrolysis capacity (alkaline electrolysis)
Energy Savings: (thermal and electricity)	Final energy savings (fossil fuel) depend on fuel and substitution rate, up to 100% possible (equalling 1500 kWh/t_{glass})
CO_2 mitigation:	Up to 75-85% possible (assuming a full substitution with hydrogen)
Advantage:	• High CO_2 mitigation possible • High process temperatures possible • Storage option for renewable energy
Disadvantage:	• Technologies not yet applied on large scale • Still high investment cost/operating cost

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[19] BTechnology readiness levels (TRLs) are a method for estimating the maturity of technologies during the acquisition phase of a program, developed at NASA during the 1970s. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of technology. TRLs are based on a scale from 1 to 9 with 9 being the most mature technology. (Wikipedia)

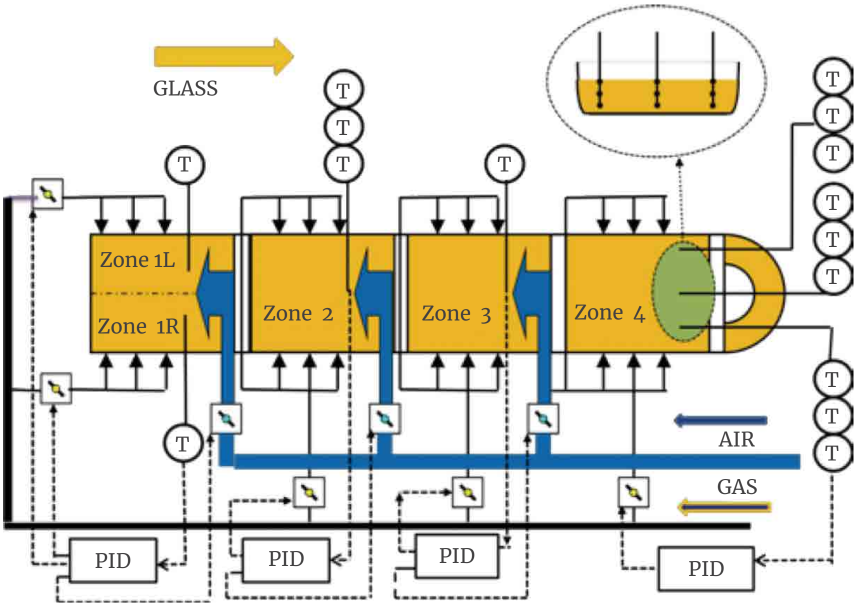
4.8 Model Based Predictive Control (MBPC)

4.8.1 Description of Baseline Situation and Energy Consumption

Modern control systems are often not solely designed for energy efficiency, but rather aim at improving productivity, product quality, or the efficiency of a production line. Applications of advanced control and energy management systems in varying development stages can be found in all industrial sectors. Control systems result in shorter residence time, reduced downtime, reduced maintenance costs, reduced processing time, and increased resource and energy efficiency, as well as improved emissions control. Application of process control systems is growing rapidly, and modern process control systems exist for virtually any industrial process. However, still large potentials exist to implement control systems, and more modern systems enter the market continuously (Backx, Ludlage, & Koenraads, 2000).

A typical forehearth control system is shown below. In each zone the glass temperature is controlled by an autonomous Proportional-Integral (PI) controller. The output of temperature sensors in each zone is transmitted to a controller, usually to a single loop PI controller or a soft controller emulated by a Supervisory Control and Data Acquisition (SCADA) system. Proportional-Integral-Differential (PID) controllers adjust the heating/cooling control actuators to bring the glass temperature back to a set point. The controllers are connected to a graphical operator interface via a proprietary network for data acquisition and off-line analysis. The matrix of nine temperature sensors located at the end of the forehearth zone number four monitors the thermal homogeneity of the glass. There is no direct connection between the control loops in the various zones (Grega, Pilat, & Tutaj, 2015).

Figure 20: A Typical Forehearth Control System (Grega, Pilat, & Tutaj, 2015)



Theoretically, the operator only sets the required temperature at the end of the forehearth channel and the control system attends to everything else. In practice, it turns out that keeping the thermal homogeneity of the molten glass under control is a difficult task due to the following points:

- The response time of the temperature control loop is quite long;
- The thermal and mechanical properties of the glass change with temperature producing nonlinear dynamics;
- The combined heating/cooling control actuators are nonlinear.

For this reason, operator action is necessary to determine the set points for each of the control zones. As the relationship between these values may significantly influence the thermal homogeneity of the glass at the end of the forehearth channel, operator's experience is an important operational factor (Grega, Pilat, & Tutaj, 2015).

4.8.2 Suggested Measures of Improvement

MBPC is a dynamic numerical model of the process, control with feedback, and fuzzy logic control. Such systems are already widely used in oil processing, but are still emerging in the glass industry (Backx, Ludlage, & Koenraads, 2000).

Continuously optimized heat input distribution leads to fuel savings. In addition, the furnace can operate continuously with little intervention from operators. The resulting stability leads to fewer defects, increased yields, increased product quality, more stable crown and bottom glass temperatures and increased furnace lifetime (Galitsky, Worrell, & Crijns-Graus, 2008).

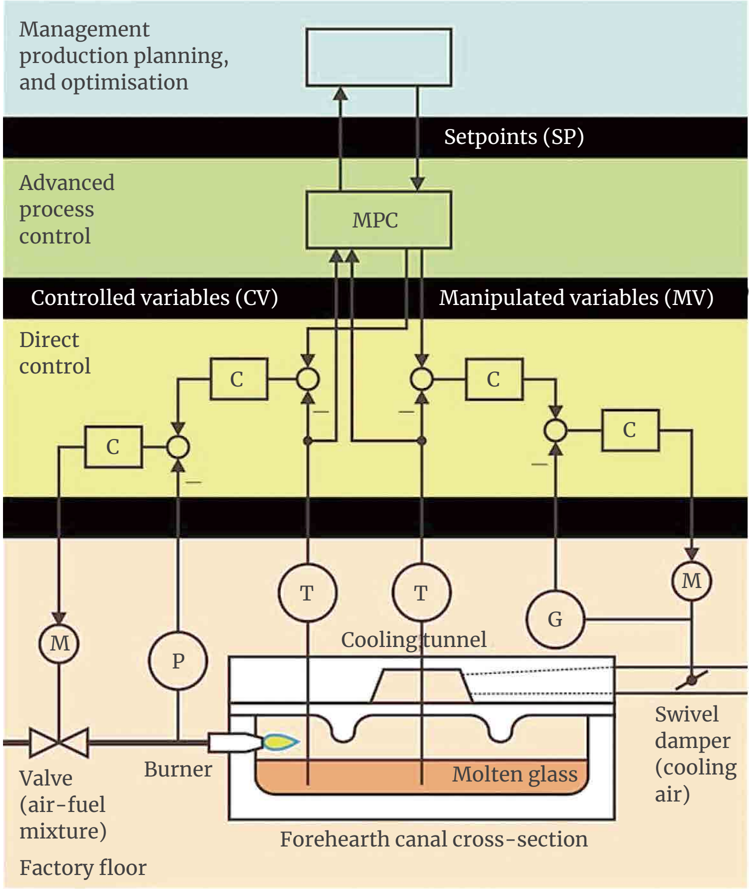
To acquire these savings, the typical forehearth control system is embedded in a complex hierarchy, which is shown in the following figure. The following points describe the three essential levels of the proposed hierarchy and are used to implement an MBPC system (Grega, Pilat, & Tutaj, 2015):

1 Process optimisation level **(blue)**: some process quality indices, such as energy consumption in steady-state, are formulated as an optimisation problem. The result of the optimisation shows the perfect glass melt temperature set points. The set points can also be automated by combining process FEM models and optimisation algorithms.

2 Predictive and multivariable process control **(green)**: A controller uses the process requirements from the optimiser level to calculate temperature set points or optimal trajectories for multiple input signals (e. g., a set of fuel flow rates of the burners) that result in optimal time dependent behaviour of multiple outputs (e. g., a set of bottom temperatures).

3 Direct control level **(yellow)**: mostly PI or PID cascade controllers.

Figure 21: Multilevel Hierarchical Structure of a Forehearth Glass Conditioning Process Advanced Control System MPC – Model Predictive Control (Grega, Pilat, & Tutaj, 2015)



MPC	Model Predictive Control		M	Servomotor		P	Pressure Sensor
C	Controller		G	Position Sensor		T	Temperature Sensor

For a control algorithm at each particular level, all the levels beneath can be considered as a generalised plant or control objects. The dynamical properties of such an equivalent plant differ considerably according to the location in the hierarchy. Hence, algorithms implemented at various levels require individual selection of the calculation time-steps (Grega, Pilat, & Tutaj, 2015).

4.8.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Installed furnace applications with MBPC show energy savings of about 2 to 3%, improved yields of about 8%, and payback periods of less than 6 months. Such systems have been installed in television, fibre, float, container and specialty glass plants in both air-fuel and oxy-fuel furnaces (Galitsky, Worrell, & Crijns-Graus, 2008). Achievable savings amount to 2.5% based on the total electrical and thermal energy consumption.

Table 15: Key facts of measure – Model Based Predictive Control (MBPC)

Key Facts of Measure – Model Based Predictive Control (MBPC)	
Investment Cost:	€200,000 per site 2 €/ t_{glass}
Energy Savings: (thermal and electricity)	46 kWh_{th}/ t_{glass}, 12.5 kWh_{el}/ t_{glass}
CO_2 mitigation:	17 kg CO_2/ t_{glass}
Advantage:	• visualization and remote access possible • glass quality improvement • better knowledge of the plant
Disadvantage:	• many technical components are necessary • difficult to implement • high analysis effort before the system can be installed

4.9 Pressure Drop Minimization

4.9.1 Description of Baseline Situation and Energy Consumption

In glass production, compressed air is used in the forming of containers, for the forming of other specialty glass products, and for tool operation. Compressed air use varies by product and from plant to plant. For container glass, electricity use for forming is estimated at 105 kWh/ton (United States Department of Energy (DOE), 2002), of which a large part is for compressed air. At a specialty glass plant producing lamps (using an electric furnace), the share of electricity used for compressed air generation was estimated at 3% of total electricity use or 7% of all non-furnace electricity consumed. (D'Antonio, Hildt, Patil, Moray, & Shields, 2003),

Compressed air is the most expensive form of energy used in an industrial plant because of its poor efficiency. Typically, efficiency from compressed air generation to end use is around 10% (Lawrence Berkeley National Laboratory (LBNL) and Resource Dynamics Corporation , 1998). Because of this inefficiency, if compressed air is used, it should be of minimum quantity for the shortest possible time. Compressed air should also be constantly monitored and reweighed against alternatives. (Galitsky, Worrell, & Crijns-Graus, 2008).

4.9.2 Suggested Measures of Improvement

An excessive pressure drop will result in poor system performance and excessive energy consumption. Flow restrictions of any type in a system, such as obstructions or roughness, results in higher operating pressures than necessary. Resistance to flow increases the drive energy on positive displacement compressors by 1% of connected power for each 2 psi of differential pressure. The highest-pressure drops are usually found at the points of use, including undersized or leaking hoses, tubes, disconnects, filters, regulators, valves, nozzles, and lubricators (demand side), as well as air/lubricant separators on lubricated rotary compressors and after-coolers, moisture separators, dryers, and filters (supply side) (Galitsky, Worrell, & Crijns-Graus, 2008).

Minimizing the pressure drop requires a systems approach in design and maintenance. Air treatment components should be selected with the lowest possible pressure drop at specified maximum operating conditions and best performance. Manufacturers' recommendations for maintenance should be followed, particularly for air filtering and drying equipment, which can have damaging moisture effects like pipe corrosion. Finally, the distance the air travels through the distribution system should be minimized. Audits of industrial facilities found that the payback period was typically shorter than 3 months for a measure to the extent of the above points (Galitsky, Worrell, & Crijns-Graus, 2008).

Further measures that improve the efficiency of the compressed air system are (Galitsky, Worrell, & Crijns-Graus, 2008):

- **Maintenance**

  Ongoing filter inspection and maintenance,
  Keeping compressor motors properly lubricated and cleaned,
  Inspection of fans and water pumps for peak performance,
  Maintaining the coolers (compressor),
  Compressor belt inspection,
  Replacing air lubricant separators,
  Checking water-cooling systems,
  Minimizing compressed air leak throughout the systems,
  Checks for excessive pressure, duration, or volume,

- **Monitoring systems typically include the following**

  Pressure gauges on each receiver or main branch line and differential gauges across dryers, filters, etc.,
  Temperature gauges across the compressor and its cooling system to detect fouling and blockages,
  Flow meters to measure the quantity of air used,
  Dew point temperature gauges to monitor the effectiveness of air dryers,
  Kilowatt-hour meters and hours run meters on the compressor drive,
  Checking of compressed air distribution systems after equipment has been reconfigured to be sure that no air is flowing to unused equipment or to obsolete parts of the compressed air distribution system,
  Checking for flow restrictions of any type in a system, such as an obstruction or roughness, which can unnecessarily raise system operating pressures,
  Checking for compressed air use outside production hours,

- **Leak reduction**

  Overall, a 20% reduction of annual energy consumption in compressed air systems is projected for fixing leaks,

- **Dimensioning and operation of the system**

  Properly sized pipe diameters, regulators and compressor motors,
  Modification of system in lieu of increased pressure and use air at lowest possible pressure,
  Turning off unnecessary compressed air and improve load management,

- **Recovery systems**

  Heat and energy recovery for air drying.

4.9.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Many of the opportunities to reduce compressed air system energy use are not prohibitively expensive; payback periods for some options are extremely short.

For example, at an Automotive Components Holdings glass plant in Nashville, Tennessee, a comprehensive energy audit and efficiency improvement campaign on its compressor systems led to leak reductions, lower operating pressures, and compressor efficiency upgrades that delivered annual savings of over $700,000 at a payback of just 1 year (United States Department of Energy (DOE), 2003). Of the $700,000 in annual savings, $300,000 were due to energy savings and $400,000 were due to reduced maintenance and labour costs resulting from the efficiency improvements (Galitsky, Worrell, & Crijns-Graus, 2008).

A similar comprehensive audit at OSRAM Sylvania's specialty glass plant in Exeter, New Hampshire (which included control strategies, leak detection, and demand reduction in its evaluation) identified opportunities for electricity savings of 164,000 kWh per year, which would lead to energy cost savings of nearly $14,000 per year (D'Antonio, Hildt, Patil, Moray, & Shields, 2003). The savings were equal to 25% of the electricity used in the compressed air system (Galitsky, Worrell, & Crijns-Graus, 2008).

3% of the total electrical energy consumption of glass production is required for the compressed air system. With this measure, 25% of the energy consumption for the compressed air can be saved.

Table 16: Key Facts of Measure – Pressure Drop Minimization

Key Facts of Measure – Pressure Drop Minimization	
Investment Cost:	€300,000 per site 3 €/ t_{glass}
Energy Savings: (thermal and electricity)	4 kWh_{th}/ t_{glass}
CO_2 mitigation:	1 kg CO_2/ $tonne_{glass}$
Advantage:	• Better knowledge of the plant because the whole compressed air system needs to be analysed
Disadvantage:	• Difficult to implement (full system analysis required)

4.10 Outlook on Further Developments

For the agreed decarbonization path of the European Union one of the greatest challenges in the upcoming years is certainly the **reduction of CO2 emissions in industrial production**[20]. The glass fibre sector – as a sub-sector of glass production – is among the **most energy-intensive sectors** and a sector with extremely high temperature process heat requirements. Thus, only addressing energy efficiency optimisation of the processes will not be sufficient to reach the target. Direct substitution of fossil fuels with renewable energy for high temperature processes is a challenging task. Most promising options are switching to electric furnaces or to hydrogen or synthetic fuels as outlined in previous chapters.

The European Glass Alliance analysed the contribution of the sector towards a climate neutral economy. In this respect, glass manufacturing in Europe has considerably decreased its specific emissions in the last 50 years: For example, the French glass industry almost reached a reduction of 70% (in tCO2 per tonne of melted glasses) between 1960 and 2010. However, further reductions are only realised at a smaller pace and are harder to realise. 75-85% of overall emissions stem from fuel combustion for high temperature heat and 15-25% are due to the decomposition of carbonates in the batch.

For the reduction of energy requirements related to high-temperature heat the European Glass Alliance points at the uptake of **best available technologies** in the furnace process and beyond, which include the greater use of **recycled glass, waste heat recovery and furnace design and operation**. Especially promising is the switch to carbon neutral resources such as biogas and electric melting. Increased cullet use not only reduces process emissions and also leads to lower energy requirements for the melting process. However, throughout the EU industry, virtually all internally generated cullet is reused – further potentials are rather in the post-consumer sector. Here main issues to be solved are the availability and affordability of good quality cullet.

Further R&D regarding the following issues is required and would be of cross-sectoral interest:

- Electrification of larger size furnaces with melting temperatures above 1000°C,
- Process emissions which cannot be addressed via energy efficiency measures only,
- Alternative heat sources for large size furnaces and alternative carbon-neutral fuels,
- Applicability of carbon capture and storage (CCS) and carbon capture utilization on site (please also refer to (ALLPLAN, 2021) for further details on CCS and CCU). (Glass Alliance Europe, 2021)

The Alliance also claims that for the realisation of available potentials also substantial public investments in relevant infrastructure and a change in the regulatory framework would be necessary. This especially relates to biogas distribution networks, hydrogen networks and the availability of carbon free electricity. (Glass Alliance Europe, 2021)

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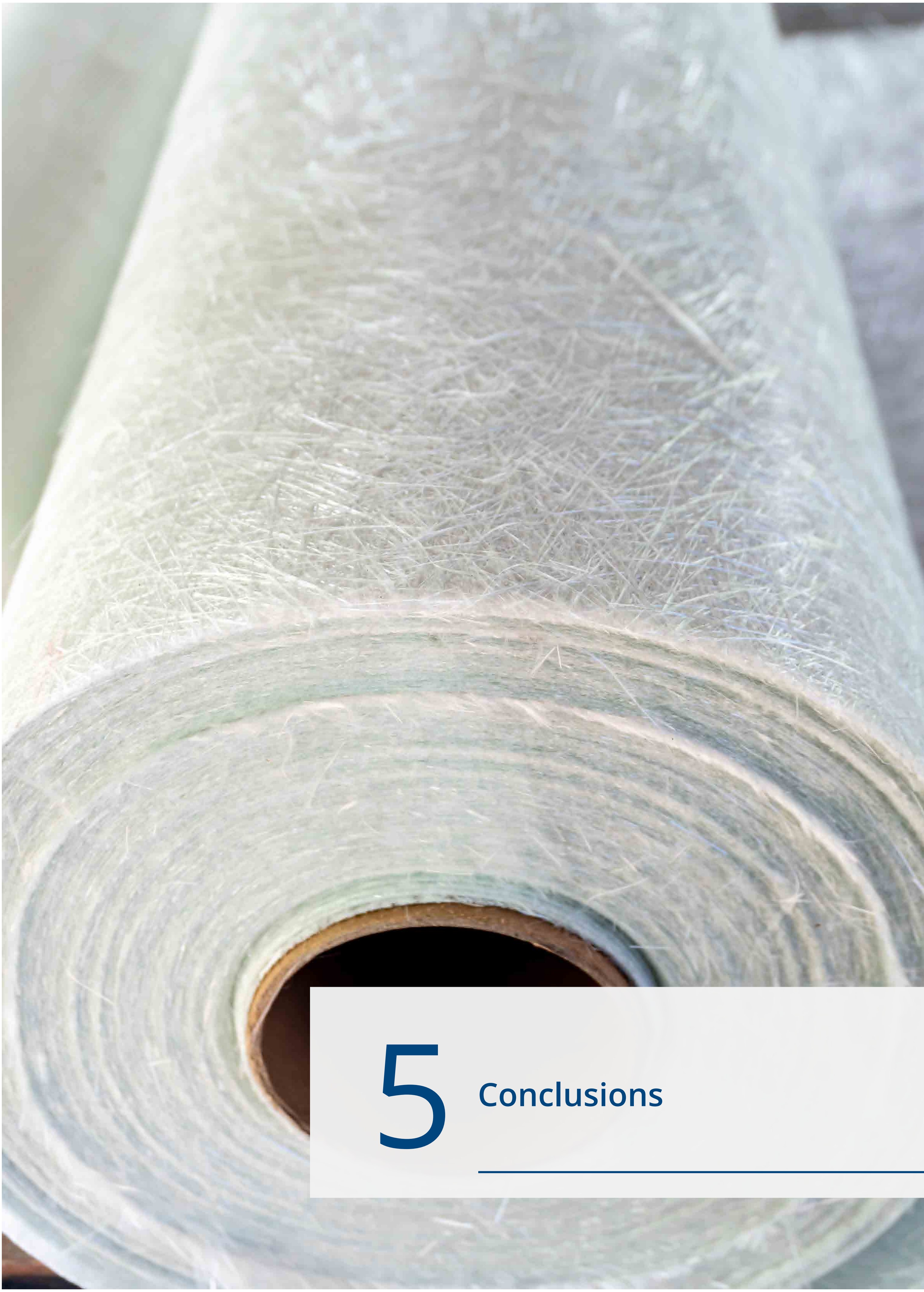
[20] Aim of climate neutrality by 2050 (net-zero greenhouse gas emissions) – refer to the European Green Deal and EU’s commitment under the Paris Agreement. (https://ec.europa.eu/clima/policies/strategies/2050_en) .



5

Conclusions

Glass (fibre) production is a highly energy-intensive process requiring process heat at **temperatures above 1600°C** with **energy requirements of around 1.8 MWh** per tonne of product. Throughout the whole production process, there is a wide range of measures available to improve energy and resource efficiency of the furnaces and to reduce CO2 emissions.

Although lower than in other sectors like cement, **process emissions** still account for **15-25 % of overall emissions**. Thus, the CO2 reduction potential via optimization of production sub-processes is limited. Measures optimizing the largest consumer – the **melting furnace** – have been described in detail and can lead to considerable savings within these sub-processes (ranging from few kWh to more than 1 MWh per tonne of glass). The largest energy conservation potential is attributable to heat recovery measures, fuel switch to carbon-neutral energy sources and process optimisations.

In the long run, major contributions in terms of CO2 reduction are expected from **carbon capture technologies** and from the **use of hydrogen, liquid biofuel and electric melting.** (Glass Alliance Europe, 2021). Most of the analysis is done on a global level for the overall glass manufacturing industry and not specifically for (the comparably small sub-sector of) glass fibre manufacturing. However, it can be assumed that overall conclusions for glass production also hold for this sector as the glass melting process as such possess the same characteristics as other sub-sectors.

Table 17: Technology Potential for Emission Reduction in Glass Manufacturing

Category of Potentials	Technology	CO_2 Reduction Potential[21]
CCS/CCU	Carbon capture	max. 90%
Fuel switch	Carbon neutral gas	75-85%
	Electric melting	75-85%
	Liquid biofuel	75-85%
	Hydrogen 20% in gas pipe	15-17%
	Hydrogen 100%	75-85%
Circular economy	Increased use of recycled glass (container glass)	max. 20%
	Increased use of recycled glass (flat glass)[22]	max. 5%
Process	Batch pelletisation	max. 5%
	Raw materials pre-heating	max. 15%
	Glass batch reformulation	max. 20%
	Waste heat recovery	max. 15%

Source: adapted from (Glass Alliance Europe, 2021)

The most promising energy saving measures have been presented throughout the report and are summarized below.

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[21] Partly mutually exclusive potentials, cannot be simply summed up: These figures are long-term maximum savings and might deviate from other assumptions relevant for currently achievable savings presented in former chapters of the report.

[22] No specific reference to glass fibre production

Table 18: Overview Key Facts

Measures	Key Facts of Measures				
	Investment Cost	Energy Savings (thermal and electricity)	CO_2 Mitigation	Advantage	Disadvantage
Optimized Fluxing Agents	n.a. (cost difference of soda ash and lithium compounds)	5-10% reduction of energy consumption in furnace: 120 kWh/t_{glass}	24 kgCO_2/t_{glass}	• Lower melting temperature, lower energy requirement • Improved forming properties and better glass quality • Cost advantage in comparison to soda ash	-
Glass (Fibre) Recycling	Cost depending on the cullet used	2.5-3% saving of furnace energy for each additional 10% of cullet used, 45 kWh/ t_{glass}	9 kg CO_2/t_{glass} for each additional 10% of cullet used	• Lower energy consumption, increased resource efficiency • Lower particulate emissions • Furnace easier to preheat • Output of the furnace can be increased	• Potential problems in the furnace due to impurities • Potential quality issues depending on the quality and composition of the cullet
Oxy-Fuel - TCR	Not known	0.22 MWh_{th}/$tonne_{glass\ fibre}$ (baseline oxy-fuel without HR)	44 kg CO_2/ t_{glass}	• Non-catalytic reforming process • Low NO_x Emission • Scalable melting technologies	• High CAPEX for relatively small incremental heat recovery at O2 recuperators
Oxy-Fuel Furnaces Regenerative (Eco-HeatOx)	~ 42 – 85 tEUR/ t_{glass}	13.8 kWh / t_{glass} (compared to baseline ColdOx)	23 kg CO_2/ t_{glass}	• Reduced energy costs • Flexible energy sourcing • Limited additional CAPEX with less than 3-year payback • Replicability and transferability potential	• Technology is still in a piloting stage
Electric Boosting	• €1.3 mill. per site • 13 €/ t_{glass}	• 750 kWh_{th}/ t_{glass} -300 kWh_{el}/ t_{glass}	-34 kg CO_2/ t_{glass}	• Glass quality improvement	• High analysis effort required before the system can be implemented
Batch and Cullet Preheating	• €2.2 mill per site • 22 €/ t_{glass}	• 225 kWh_{th}/ t_{glass} 225 kWh_{e}l t_{glass}	45 kg CO_2/ t_{glass}	• Approved simple technology for 30 years • removed SO, HCl, and HF from the waste gases	• Large space requirements • Deteriorated preheater (corrosion and high temperatures)

Measures	Key Facts of Measures				
	Investment Cost	Energy Savings (thermal and electricity)	CO_2 Mitigation	Advantage	Disadvantage
Low Carbon Fuels (Hydrogen and Synthetic Methane)	800-1500 € per kW electrolysis capacity (alkaline electrolysis)	Final energy savings (fossil fuel) depending on fuel substituted and substitution rate, up to 100% (would be appr. 1500kWh/t)	Up to 75-85% (when using 100% Hydrogen)	• High CO_2 mitigation possible • High process temperatures possible • Storage option for renewable energy	• Technologies not yet applied on large scale • Still high investment cost/operating cost
Model Based Predictive Control (MBPC)	• €200,000 per site • 2 €/ t_{glass}	• 46 kWh_{th}/ t_{glass} • 12.5 kWh_el/ t_{glass}	17 kg CO_2/ t_{glass}	• Visualization and remote access possible • Glass quality improvement • Better knowledge of the plant	• Many technical components are necessary • Difficult to implement • High analysis effort before the system can be installed
Pressure Drop Minimization	• €300,000 per site • 3 €/$tonne_{glass\ fibre}$	• 4 kWh_{th}/$t_{glass\ fibre}$ • 4 kWh_el/$t_{glass\ fibre}$	1 kg CO_2/ t_{glass}	• Better knowledge of the plant because the whole compressed air system needs to be analysed	• Difficult to implement (full system analysis required)

Literature

Akviran, M. (2016). *LIFE Eco-HeatOx Layman's report* . LIFE12 ENV/BG/000756 European Community .

ALLPLAN. (2021). *Technical Guidelines on German and Internationally Advanced Energy Efficiency Measures in the Airport, Cement, Ceramics, Glass Fibre and Pulp and Paper Industry, Sector Report Pulp & Paper.* GIZ.

Backx, T., Ludlage, J., & Koenraads, A. (2000). *Application of Model Predictive Control for Quality Control of Glass Melting Processes. IPCOS Technology.* Netherlands: http://www.esat.kuleuven.ac.be/~HK05/les4/icg2000.pdf.

Barklage-Hilgefort, H. (2009). *Batch Preheating on Container Glass Furnaces.* New York, USA: 69th Conference on Glass Problems: Ceramic Engineering and Science Proceedings, John Wiley & Sons.

Beerkens, R. (2009). *Energy Saving Options for Glass Furnaces and Recovery of Heat from Their Flue Gases.* New Yourk, USA: 69th Conference on Glass Problems: Ceramic Engineering and Science Proceedings, John Wiley & Sons.

Bruno Lapillonne, K. P. (2018). Regional training on indicators « ODYSSEE-MURE » 2. Energy efficiency trends by sector: ODEX.

Caumont-Prim, C., Paubel, X., Juma, S., & Jarry, L. (2018). *www.lifecleanox.com.* Abgerufen am 20.10.2021 von www.lifecleanox.com: https://www.lifecleanox.com/sites/cleanox/files/2018/05/30/extractpage_glass_worlwide_may-june_2018.pdf

Chakravarti, S., Alexander, J., & Kobayashi, H. (2021). WASTE HEAT RECOVERY IN OXY-FUEL GLASS FURNACES –A PATH TO SUSTAINABILITY AND LOWER CO2 EMISSIONS. *81st Conference on Glass Problems* (S. 121 - 135). S.K. Sundaram (Ed.). https://doi.org/10.1002/9781119823056.ch12.

D'Antonio, M., Hildt, N., Patil, Y., Moray, S., & Shields, T. (2003). *Energy Efficiency Opportunities in the Glass Manufacturing Industry. Proceedings of the ACEEE Summer Study*. New York: Rye Brook.

DENA. (2017). *Roadmap Power to Gas.*

DENA. (2018). *Heutige Einsatzgebiete für Power Fuels Factsheets zur Anwendung von klimafreundlich erzeugten synthetischen Energieträgern.*

Dolianitis, I., Giannakopoulos, D., Hatzilau, C.-S., Karellas, S., Kakaras, E., Nikolova, E., . . . Zitounis, T. (2016). *Waste heat recovery at the glass industry with the intervention of batch and cullet preheating.*

EnArgus. (01. 10 2021). *Glasfaserherstellung.* Von https://www.enargus.de/pub/bscw.cgi/d4454-2/*/*/Glasfaserherstellung.html?op=Wiki.getwiki abgerufen

European Commission. (2018, last update 12/2020). *Clean energy for all Europeans package.* Von https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en#energy-efficiency abgerufen

European Commission. (2021). *COMMISSION IMPLEMENTING REGULATION determing revised benchmark values for free allcoation of emission allowances for the period from 2021 to 2025 pursuant to Article 10a(2) of Directive 2003/87/EC of the European Parliament and of the Council (draft).*

Fawkes, S. O. (2016). *Best Practices and Case Studies for Industrial Energy Efficiency Improvement – An Introduction for Policy Makers.* Copenhagen: UNEP DTU Partnership.

Fraunhofer ISI. (2018). *Energy Efficiency Trends and Policies in Germany – An Analysis Based on the ODYSSEE and MURE Databases.*

Galitsky, C., Worrell, E., & Crijns-Graus, W. (2008). *Energy Efficiency Improvement and Cost Saving Opportunities for the Glass Industry. An ENERGY STAR Guide for Energy and Plant Managers.* https://www.researchgate.net/publication/236372948.

Glass Alliance Europe. (2021). *PANORAMA OF THE EU GLASS INDUSTRY.* Von https://www.glassallianceeurope.eu/images/cont/panorama-2020-eu27_file.pdf abgerufen

Glass Alliance Europe. (04. 10 2021). *The European glass sector contribution to a climate neutral economy, Position paper v.2.* Von https://www.glassallianceeurope.eu/images/cont/2021-05-05-gae-position-paper-on-decarbonisation-v2_file.pdf abgerufen

Gonzalez, A., Solorzano, E., Laux, S., Iyoha, U., Wu, K., & H. Kobayashi. (2016). Operating Experience with Optimelt™ Regenerative Thermo-Chemical Heat Recovery for Oxy-Fuel Fired Glass Furnaces. *76th Conference on Glass Problems* (S. 17 - 25). S.K. Sundaram (Ed.). https://doi.org/10.1002/9781119282471.ch2.

Grega, W., Pilat, A., & Tutaj, A. (2015). *Modelling of the Glass Melting Process for Real-Time Implementation.* International Journal of Modeling and Optimization.

Hubert, M. (2015). *IMI-NFG Course on Processing in Glass, Lecture 3: Basics of industrial glass melting furnaces.* Von https://www.lehigh.edu/imi/teched/GlassProcess/Lectures/Lecture03_Hubert_industglassmeltfurnaces.pdf abgerufen

IEA. (2018). *IEA data and statistics.* Von https://www.iea.org/data-and-statistics abgerufen

Institute for Industrial Productivity. (14. 04 2021). *Industrial Efficiency Technology Database.* Von http://www.iipinetwork.org/wp-content/Ietd/content/cement.html abgerufen

Kim, H., Kang, T., Kaiser, K., Liedel, S., Jarry, L., Paubel, X., . . . Kaya, L. (2016). Heat Oxy-combustion: an Innovative Energy Saving Solution for Glass Industry. *76th Conference on Glass Problems*: (S. 149 - 155). S. K. Sundaram, https://doi.org/10.1002/9781119282471.ch12.

Kim, K.-D. H.-H. (2011). *Recycling of TFT-LCD cullet as a raw material for fibreglasses; Glass Technology - European Journal of Glass Science and Technology part A, Volume 52, Number 6.*

Kobayashi, H., Gonzalez, A., Solorzano, E., Lagos, C., Lugo, G., S. Laux, K. W., . . . Francis, A. (2015). Optimelt™ Regenerative Thermo-Chemical Heat Recovery for Oxy-Fuel Glass Furnaces. *75th Conference on Glass Problems* (S. 113 - 120). S.K. Sundaram (Ed.).

Königsreuther, P. (29. 06 2020). *Glasfaserproduktion: jetzt wird die Glasfasererstellung für Kunststoffe nachhaltiger.* Von https://www.maschinenmarkt.vogel.de/jetzt-wird-die-glasfaserherstellung-fuer-kunststoffe-nachhaltiger-a-943664/ abgerufen

LAGA. (2019). *Entsorgung faserhältiger Abfälle, Abschlussbericht Juli 2019.*

Lawrence Berkeley National Laboratory (LBNL) and Resource Dynamics Corporation . (1998). *Improving Compressed Air System Performance, a Sourcebook for Industry.* U.S. Department of Energy, Motor Challenge Program.

Leisin, M. (2019). *Energiewende in der Industrie, Potenziale und Wechselwirkungen mit dem Energiesektor, Branchensteckbrief der Glasindustrie, Bericht an: Bundesminieriumg für Wirtschaft und Energie, in Zusammenarbeit mit Navigant Energy Germnay GmbH.*

Liquide, A. (2017). *www.ecoheatox.com*. Abgerufen am 15.10.2021 von www.ecoheatox.com: https://www.ecoheatox.com/sites/ecoheatox/files/2017/06/28/nexelia_g_melting-heat_oxy-combustion_offer_sheet_v5.pdf

Marcel Fiehl et al. (2017). *Biogas as a co-firing fuel in thermal processing industries: implementation in a glass melting furnace.* Essen.

ODYSSEE Database. (2018). Von https://www.odyssee-mure.eu/ abgerufen

R. Krijgsman, M. M. (2019). *Decarbonisation Options for the Dutch Glass Fibre Industry.*

Reynolds, A. (2018). *Electric Boosting and Melting Technology - Overview of developments and current work programs at FSL* . fives group.

Scalet Bianca Maria, G. M. (2013). *Best Available Techniques (BAT) Reference Document for the Manufacture of Glass.*

Stormont, R. (2010). *Electric melting and boosting for glass quality improvement*. Glass Worldwide.

Suhr, M., Klein, G., Kourti, I., Gonzalo, M. R., Santonja, G. G., Roudier, S., & Sancho, L. D. (2015). *Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board* . Luxembourg: European Commission .

Szczeniak, J., Bauer, C., & Kober, T. (2020). *Industry - Glass*. DEEDS.

United States Department of Energy (DOE). (2002). *Energy and Environmental Profile of the Glass Industry.* Washington, DC.: ffice of Industrial Technologies, Department of Energy.

United States Department of Energy (DOE). (2003). *Compressed Air System Upgrade Improves*. Washington, D.C.: Office of Industrial Technologies.

US. Department of Energy, Office of Energy Efficiency & Renewable Energy. (2017). *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Glass Fiber Reinforced Polymer Manufacturing.*

Wallenberger, F., Watson, J., & Li, H. (2001). *ASM Handbook Glassfibre*. PPG Industries, Inc.

WKO, Fachverband der Glasindustrie Österreich. (2019). *Jahresbericht 2019*.

Zier Michael, P. S. (May 2021). A review of decrbonizatin options for the glass industry. *Energy Conversion and Management: X, www.sciencedirect.com/journal/energy-conversion-and-management-x.*

Zippe, P. (2011). *Recent Developments of Batch and Cullet Preheating in Europe - Practical Experiences and Implications.* New York, USA: 71st Conference on Glass Problems: Ceramic Engineering and Science Proceedings, John Wiley & Sons.

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