Energy Conversion and Management: X 17 (2023) 100336

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

Industrial decarbonization pathways: The example of the German glass industry

Michael Zier [a,b,*], Noah Pflugradt [a,b], Peter Stenzel [c], Leander Kotzur [a,b], Detlef Stolten [a,b,d]

[a] Institute of Techno-economic Systems Analysis (IEK-3), Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Str., Jülich D-52428, Germany
[b] Jülich-Aachen Research Alliance, JARA-Energy, Jülich, Aachen, Germany
[c] Cologne Institute for Renewable Energy (CIRE), Technische Hochschule Köln, Betzdorfer Straße 2, Cologne 50679, Germany
[d] Chair for Fuel Cells, RWTH Aachen University, c/o Institute of Techno-economic Systems Analysis (IEK-3), Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Str., Jülich D-52428, Germany

ARTICLE INFO

Keywords:
CO_2 budget
CO_2 reduction targets
Industrial transformation pathways
Fuel switch
Glass industry
Decarbonization
Energy efficiency

ABSTRACT

Mitigating anthropogenic climate change and achieving the Paris climate goals is one of the greatest challenges of the twenty-first century. To meet the Paris climate goals, sector-specific transformation pathways need to be defined. The different transformation pathways are used to hypothetically quantify whether a defined climate target is achievable or not. For this reason, a bottom-up model was developed to assess the extent of selected industrial decarbonization options compared to conventionally used technologies from an emissions perspective. Thereby, the bottom-up model is used to analyze the German container and flat glass industries as an example. The results show that no transformation pathway can be compatible with the 1.5 °C based strict carbon dioxide budget target. Even the best case scenario exceeds the 1.5 °C based target by approximately + 200 %. The 2 °C based loose carbon dioxide budget target is only achievable via fuel switching, the complete phase-out from natural gas to renewable energy carriers. Furthermore, the results of hydrogen for flat glass production demonstrate that missing investments in renewable energy carriers may lead to the non-compliance with actually achievable 2 °C based carbon dioxide budget targets. In conclusion, the phase-out from natural gas to renewable energies should be executed at the end of the life of any existing furnace, and process emissions should be avoided in the long term to contribute to 1.5 °C based strict carbon dioxide budget target.

1. Introduction

The anthropogenic climate change has been scientific consensus for at least two decades [1,2]. Immediate consequences pose natural (e.g., extreme heat, freshwater availability), societal (e.g., health, employment), and economic threats [3]. The extent and frequency of damages induced by the anthropogenic climate change correlate to the global mean temperature, which in turn increases with atmospheric carbon dioxide (CO_2) concentrations [4]. Therefore, CO_2 budgeting is a common way to describe climate targets and according to the Intergovernmental Panel on Climate Change (IPCC), the global 67th percentile value to achieve the 1.5 °C target is a remaining quantity of 420 Gt_{CO2} from January 2018 on [4]. To meet the 1.5 °C target, sector-specific transformation pathways that clearly define the decarbonization timeline are imperative.

In general, decarbonization is concerned at how to establish a carbon-free economy to avoid carbon dioxide emissions [5]. Two typical research areas associated with decarbonization involve energy systems modeling [6] and the design of a carbon market and a carbon price [7]. The vast majority of the energy system modeling research agrees on the massive expansion of photovoltaic and wind energy as early as possible in the decarbonization timeline while phasing out fossil-fuel power generation [8]. Issues such as the nature and design of grid-connected infrastructure [9,10] or energy storage technology [9], or the transformation of the industrial sector are more controversially discussed [11]. In addition, there is a variety of research topics in the

Abbreviations: BV Glas, Federal Association of the German Glass Industry Bundesverband Glasindustrie e.V.; CAGR, Compound annual growth rate; CCS, Carbon capture and storage; CCU, Carbon capture and utilization; CO_2, Carbon dioxide; DAC, Direct air capture; DEHSt, German Emissions and Trading Authority; LHV, Lower heating value; MIP, Missed investment periods; PPA, Power purchase agreement; *SEC*, Specific energy consumption; TRL, Technology readiness level.

* Corresponding author.
E-mail address: m.zier@fz-juelich.de (M. Zier).

https://doi.org/10.1016/j.ecmx.2022.100336
Received 8 November 2021; Received in revised form 21 November 2022; Accepted 25 November 2022
Available online 30 November 2022

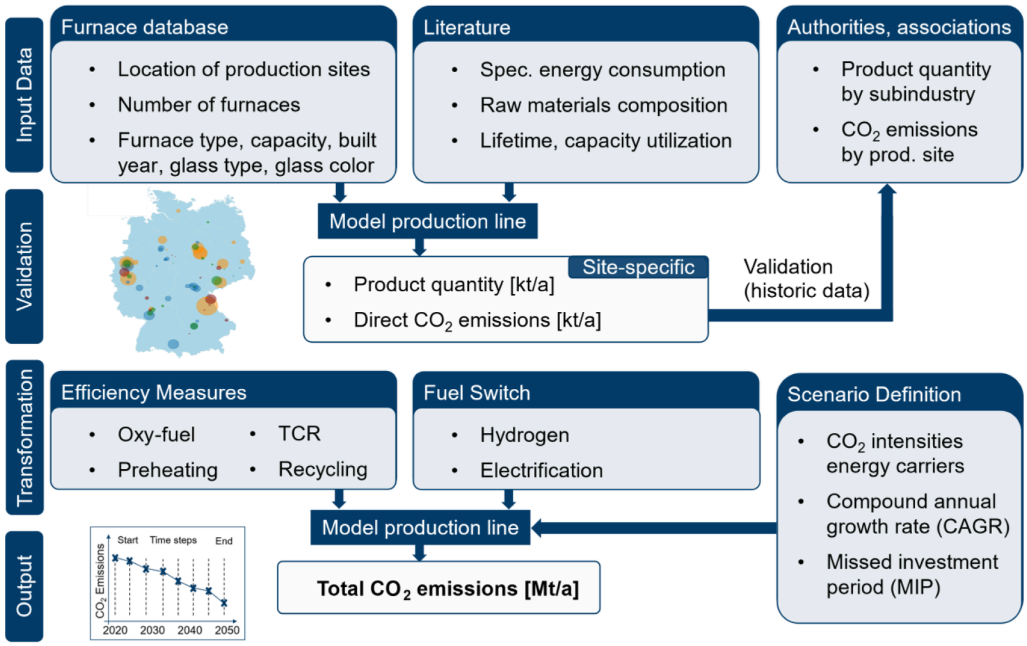

Fig. 1. Simplified procedure - key input data, model validation and prediction of future CO_2 transformation paths based on the validated model.

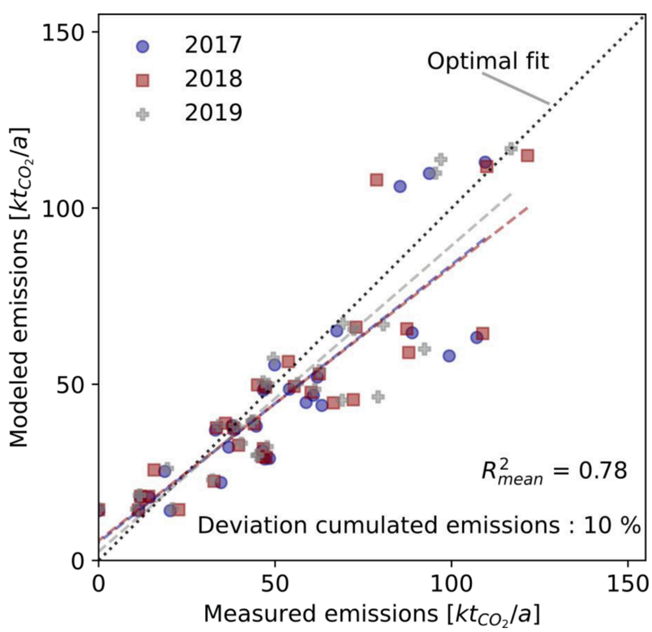

Fig. 2. Direct CO_2 emissions of German container glass production sites, modeled, and listed at DEHSt. R^2_{mean} was averaged as to the years. The mean slope deviation indicates the difference between the slope of the regression model and the slope of the optimal fit.

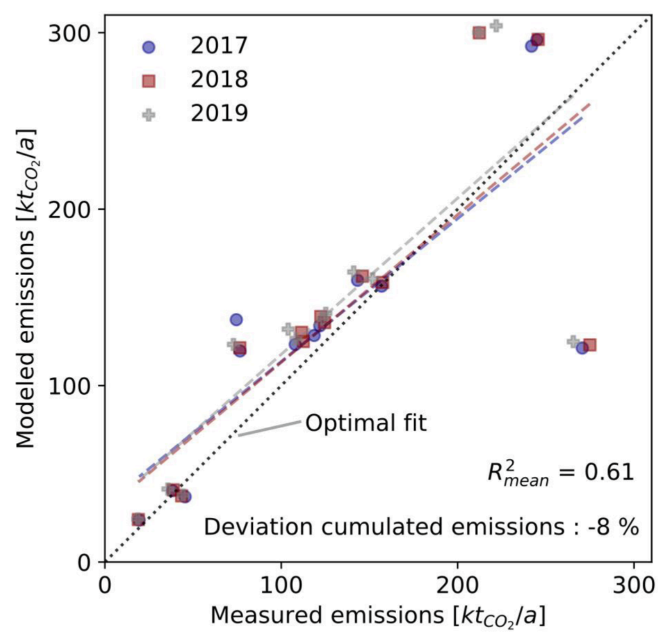

Fig. 3. Direct CO_2 emissions of German flat glass production sites, modeled, and listed at DEHSt. R^2_{mean} was averaged as to the years. The mean slope deviation indicates the difference between the slope of the regression model and the slope of the optimal fit.

decarbonization ecosystem that examine incentive mechanisms such as carbon contracts for difference [12] or white certificates [13] or that identify potential positive effects such as energy patents [14], for instance.

Energy-intensive industries are particularly challenging, as they can be characterized as capital-intensive, cost-competitive and sensitive to product quality [15]. In addition, the duration of investment periods are relatively long. Therefore, current investment decisions, have far-reaching effects on future carbon dioxide balances. Part of the energy-intensive industries is the glass industry, where most of the energy is used for process heat at high temperature levels (1400–1650 °C) to melt the raw materials [16]. The glass industry's greenhouse gas emission share in global materials production is only 4 %, but its emission growth rate belongs to the highest in the industrial sector posing a major challenge in view of the climate targets. Though specific CO_2 emissions in industrialized countries have been steadily reduced in the past [17], glass industry's absolute emissions have increased by about 165 % in the period from 1995 to 2015 [18]. The largest segments of the glass industry, container glass and flat glass, comprise about 80 % of each global, European, and German glass production, with annual emissions of 86 Mt CO2 in 2014 [19], 18 Mt CO2 in 2019 [20] and 3.2 Mt CO2 in 2019 [21], respectively. In a global comparison of the sub-industries, the

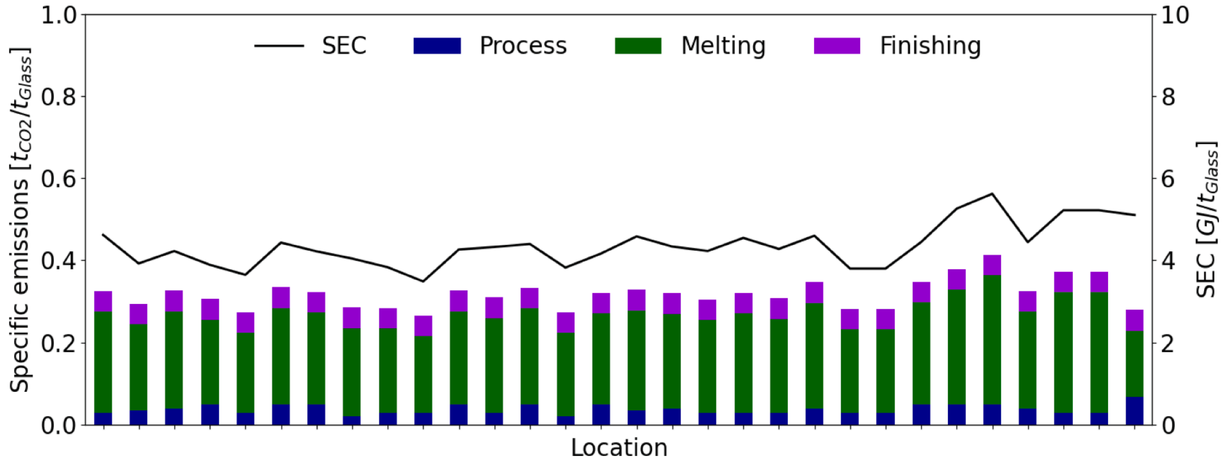

Fig. 4. Distributions of specific CO_2 emissions and specific combustion-related energy consumption (*SEC*) for German container glass locations simulated for 2019.

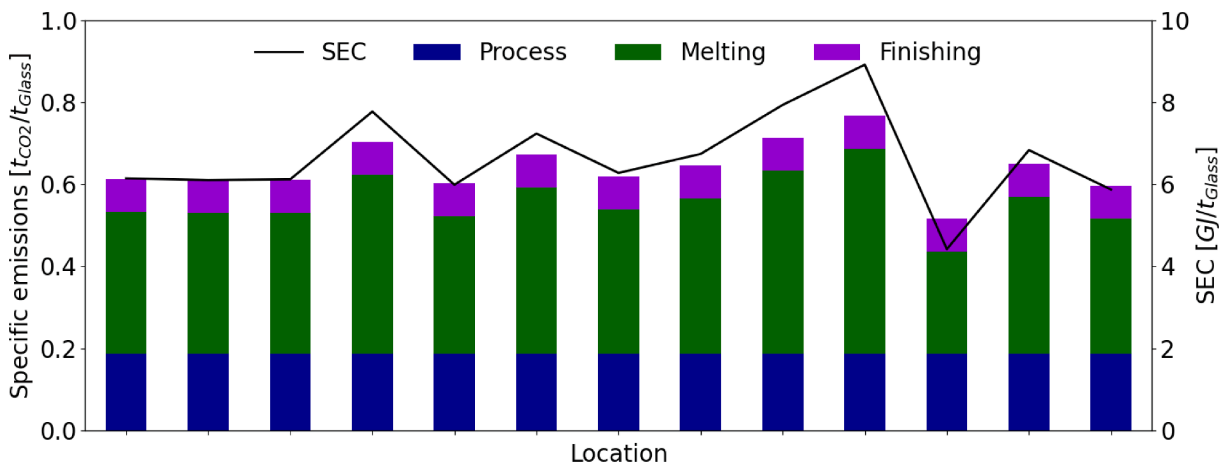

Fig. 5. Distributions of specific CO_2 emissions and specific combustion-related energy consumption (*SEC*) for German flat glass locations simulated for 2019.

Table 1
Furnace types, energy carriers and assumed efficiency improvements for different technical transformations. Exclusively the all-electric option has an additional 55% cullet limitation. All other options are subject to cullet limitations as shown in Table G4.

Name	Furnace type	Energy carrier	Efficiency improvement
Business as usual	Existing	Existing	–
Oxy-fuel	Oxy-fuel	Natural gas	Container: Fig. G1 Flat: 10 %
Cullet preheating	Existing	Existing	15 %
TCR	Regenerative	Natural gas	30 %
All-electric	Cold top electric furnace	Electricity	Container: Fig. G1 Flat: 4.4 GJ/t_{Glass}
Hybrid electric + hydrogen	Warm top electric melter	Hydrogen + electricity	*SEC* as for all-electric Allocation: 70 % electric, 30 % hydrogen
Hydrogen	Air-regenerative	Hydrogen	
Hydrogen efficient	Oxy-fuel	Hydrogen	30 %

container and flat glass industries each show a large overlap of key characteristics, such as furnace type, furnace capacity or type of forming process [22]. However, process parameters representative for different countries, such as specific energy consumption, cullet share or energy carrier differ substantially [23–26].

Table 2
Assumptions for compound annual growth rate (CAGR) and missed investment periods (MIPs). The values in bold define base assumptions, the other parameters are investigated in the context of a sensitivity analysis (data from [23,32]).

		Container	Flat
CAGR	%	−0.5, **0**, 0.5	**0**, 0.5, 2
MIP	–	**0**, 1	

There are several scientific contributions discussing a wide variety of technical options to decarbonize the glass industry, essentially focusing on energy efficiency measures or the substitution of fossil fuels with renewable energy carriers. Schmitz et al. [24] collected the average energy consumption and CO_2 emissions of different glass types for different countries in the European Emissions Trading Scheme (EU ETS). Frassine et al. [25] designed a bottom-up model to forecast the energy demand for European glass melting furnaces within a time frame from 2015 to 2030. The simulation considered impacts of aging, cullet recycling rates, and energy efficiency measures (EEMs) such as process control or selective batching.

However, studies that examine the impact of decarbonization options with respect to the development on future CO_2 emissions of existing, national industry segments, considering real production sites, are not available and thus represent a research gap. Therefore, a bottom-up model was developed, which maps the entire production process from raw materials preparation to the finished product (production

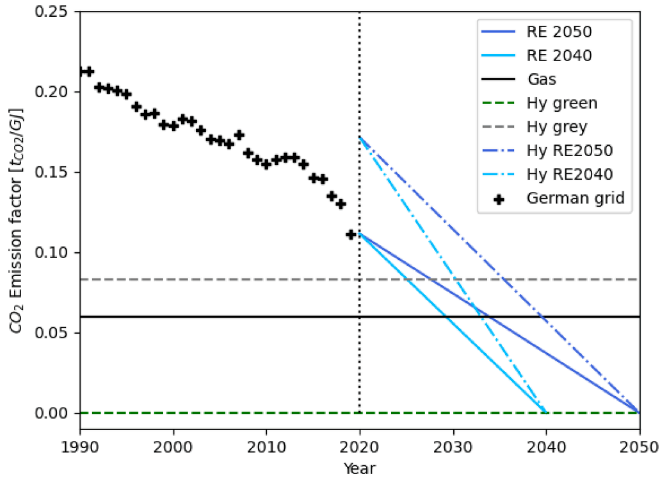

Fig. 6. Historical CO_2 emission factors for the German electricity grid and assumed CO_2 emission factor development for different energy carriers (historical data from: [33]).

line). Thereby, the German container and flat glass industries are used as an example. The model was validated on the one hand with the aid of CO_2 emission data recorded by the German Emissions and Trading Authority (DEHSt). On the other hand, the total amount of packed glass was compared with the data from the Federal Association of the German Glass Industry (BV Glas). Subsequently, transformation pathways that consider fuel switch or energy efficiency options were simulated and their impacts quantified, while considering melting furnace lifetimes and their future mortality lines.

2. Method

The method is designed to map future CO_2 emissions under varying technical decarbonization options and external scenario assumptions of a certain industrial sector in an arbitrary area, e.g., a country or a continent. First, the required the model implementation are explained in Section 2.1. Subsequently, the validation of the model is described in Section 2.2 and the selection of the transformation paths is illustrated in Section 2.3.

Fig. 1 provides an overview of the general procedure. The foundation of the input data is a furnace database [26] containing site-specific data attributes such as furnace type, furnace capacity or product type to the selected energy-intensive process (cf. Table A1). In addition, literature data is used to define production lines by individual processes, where each process handles attributes such as specific energy consumption, energy carriers and raw materials to model energy- and process-related emissions. The bottom-up model has been validated on historic product quantities and direct CO_2 emissions. Finally, the effect of different technical efficiency measures and fuel switch options as well as external scenario assumptions on future CO_2 emission trajectories are evaluated considering current plants and their lifetimes.

2.1. Model setup

The developed bottom-up model maps CO_2 emissions of a production line using an object-oriented structure that is shown in Fig. B1. The total emissions $CO_{2\ pl,\ ts}^{total}$ f a production line pl within a time step ts result from the sum of emissions that occur in each process step ps, differentiating process-related, $CO_{2\ ps,\ ts}^{process}$, nd energy-related, $CO_{2\ ps,\ ts}^{energy}$ emissions:

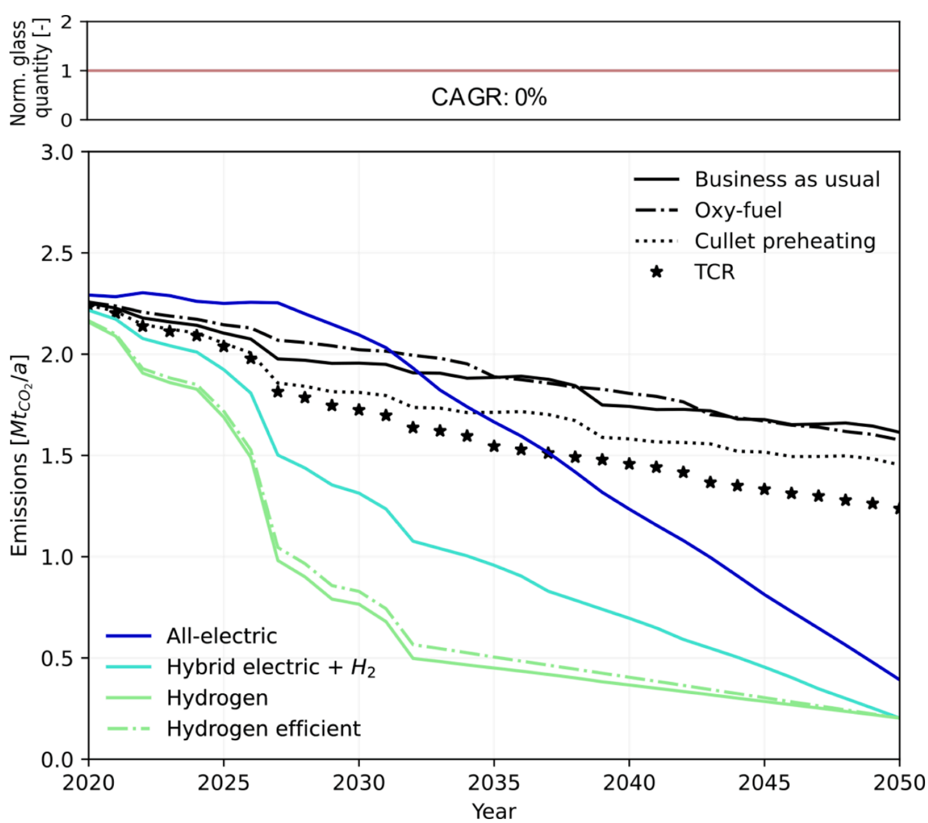

Fig. 7. Total CO_2 emissions of the German container glass industry for different technical scenarios while considering the base scenario assumptions (CAGR = 0 %, MIP = 0, renewable electricity until 2050 and green hydrogen, cf. Table D1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

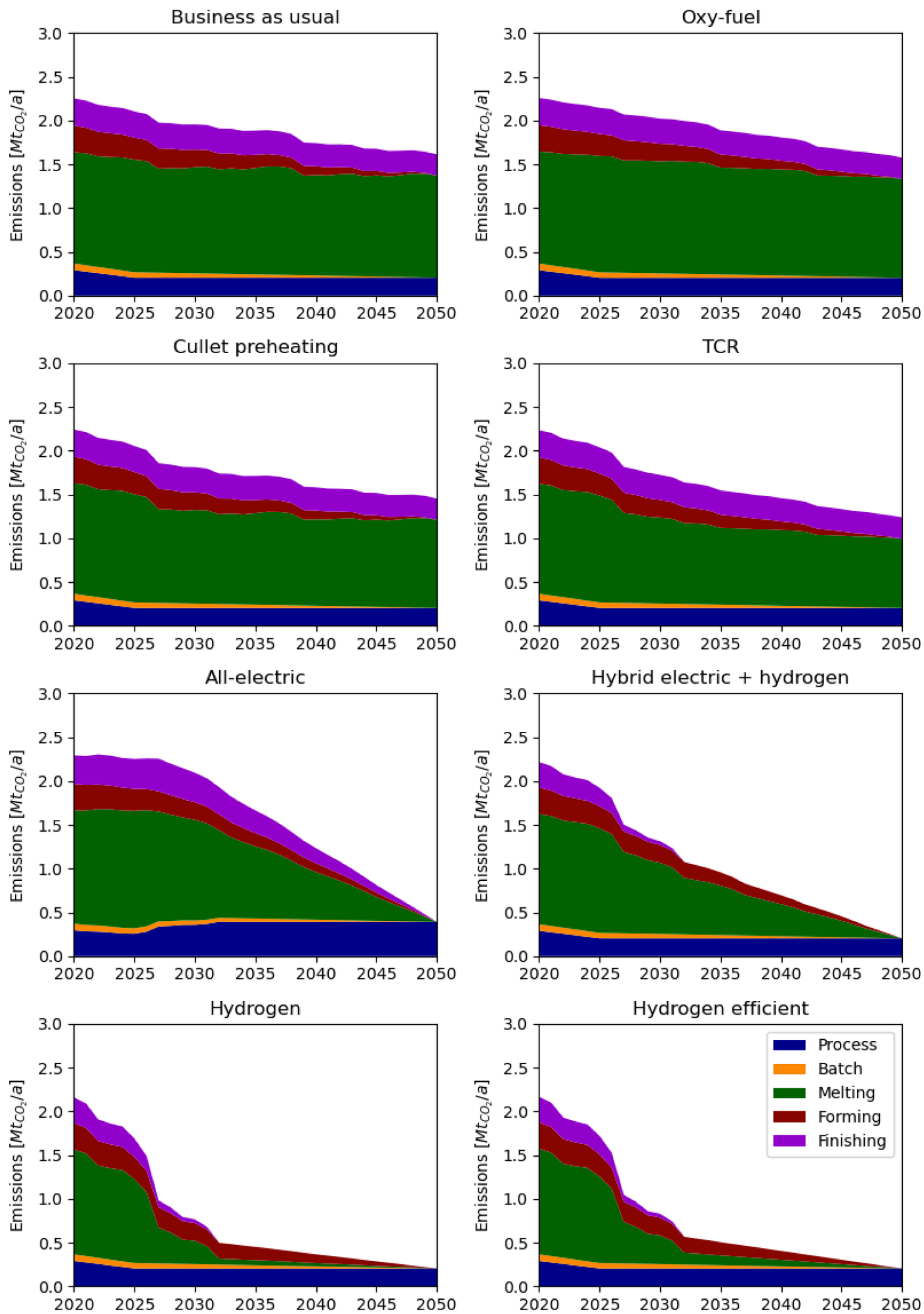

Fig. 8. CO_2 emissions of the German container glass industry by process step for different technical scenarios while considering the base scenario assumptions regarding CAGR, investment periods and energy supply (cf. Table D2).

$$CO_{2\ pl,\ ts}^{total} = CO_{2\ pl,\ ts}^{process} + \sum_{ps\ \in\ pl} CO_{2\ ps,\ ts}^{energy} \qquad \forall\ pl,\ ts$$

default, a time step of one year is set and, depending on the case study,he emissions of the production lines of a region, a country or a continent are aggregated as illustrated in Fig. B2. Process-related emissions evolve as a by-product resulting from chemical reactions designed for the production of the main product and are determined by the output of a product-specific factor $f_{pl,\ ts}^{process}$ the recycling rate $r_{pl,ts}$ and the production quantity $p_{pl,ts}$

$$CO_{2\ pl,\ ts}^{process} = f_{pl,\ ts}^{process} \cdot \left(1 - r_{pl,ts}^{actual}\right) \cdot p_{pl,ts} \qquad \forall\ pl,\ ts$$

is essentially dependent on the raw material composition that is selected for the product design. The greater the recycling rate r of a product, the lower the process-related emissions. For a 100 % recycling rate, process-related emissions are completely avoided. If the production quantity is not directly accessible, it is estimated using the given production capacity cap_{pl} nd an average utilization factor $f_{pl,\ ts}^{utilization}$ which is typical in the considered industrial sector:

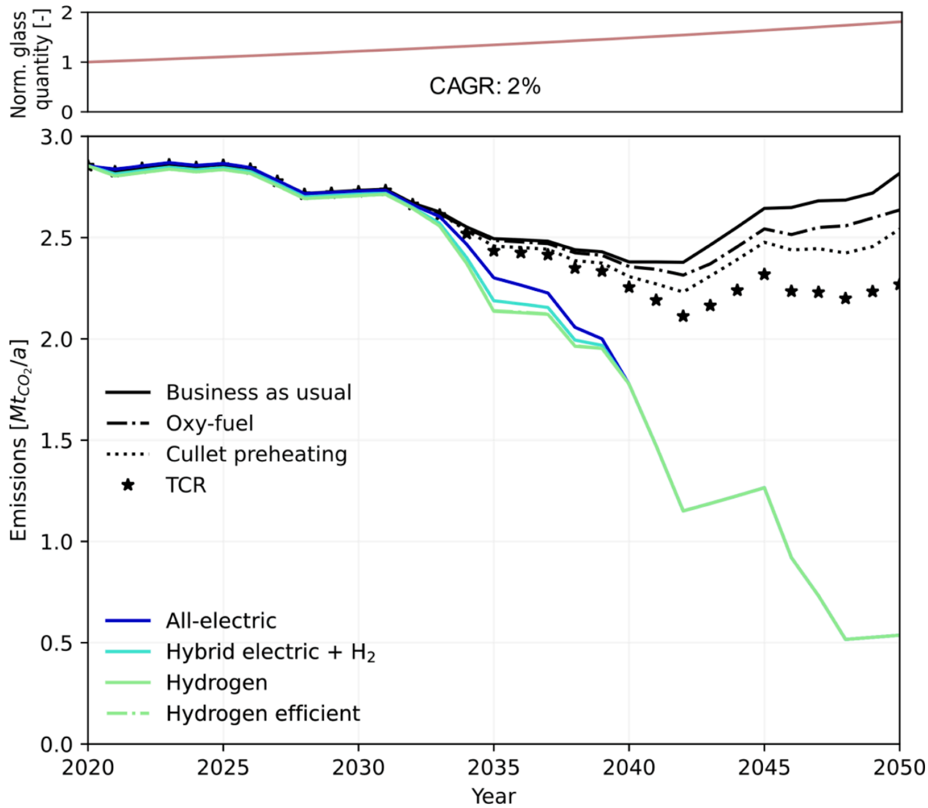

Fig. 9. Total CO_2 emissions of the German flat glass industry for different technical scenarios while considering the extreme scenario assumptions (CAGR = 2 %, MIP = 1, renewable electricity until 2040 and green hydrogen, cf. Table D2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$p_{pl,ts} = cap_{pl} \cdot f_{pl,\ ts}^{utilization} \quad \forall\ pl,\ ts$$

ergy-related CO_2 emissions result from the specific energy consumption $SEC_{ps,ts}$ production quantity $p_{pl,ts}$ nd CO_2 intensity of the employed energy source$f_{ps,\ ts}^{CO2\ intensity\ energy}$:

$$CO_{2,\ energy,\ ps,ts} = SEC_{ps,ts} \cdot p_{pl,ts} \cdot f_{ps,\ ts}^{CO2\ intensity\ energy} \quad \forall\ ps,\ ts$$

general, the specific energy consumption $SEC_{ps,ts}$ epends on the applied technology. Thereby, the specific energy consumption of a particular technology varies with different process parameters such as plant size or production quantity $p_{pl,ts}$ the recycling rate r, plant lifetime and corresponding aging effects a, or additional efficiency measures e, the latter three being represented by the correction factors cf_r, cf_a ndcf_e.

$$SEC_{ps,ts} = f(p, r, a,\ e) = f\left(p_{pl,ts}\right) \cdot cf_r \cdot cf_a \cdot cf_e \quad \forall\ ps,\ ts$$

Especially for high-temperature processes, the specific energy consumption $SEC_{ps,ts}$ ecreases with increasing production quantity due to the decreasing surface-to-volume ratio and consequently lower heat losses. Based on thermodynamic calculations or literature data, $SEC_{ps,ts} = f\left(p_{pl,ts}\right)$ an be specified, which refer to parameters significantly influencing the energy consumption, such as the recycling rate of secondary raw materials or the lifetime of a plant. Recycling of secondary raw materials is favorable from an efficiency point of view since no energy has to be provided for chemical reactions and released gases. For a determined specific energy consumption $SEC_{ps,ts} = f\left(p_{pl,ts}\right)$ ith a given recycling rate $r^{f(p)} SEC_{ps,ts}$ n be normalized with actual the recycling rate $r_{pl,ts}^{actual}$ sing an energy savings factor $f_r^{energySaving}$ epresentative for the process, with the savings in this example referring to 10 percent recycling change:

$$cf_r = 1 + \left(r^{f(p)} - r_{pl,ts}^{actual}\right) \cdot \frac{f_r^{energySaving}}{10}$$

addition, aging effects have to be considered, which usually show a non-linear behavior, but are often described by a linear relation due to an insufficient data basis. The linear relation can be described with linear aging factor $f^{linearAging}$ the actual year aY s well as the built year bY nd lifetime lt f a plant. It must be evident for which year $SEC_{ps,ts} = f(p)$ given, where the following equation assumes, as an example, that $SEC_{ps,ts}$ specified for half of the lifetime:

$$cf_a = \left(1 + f^{linearAging}\right)^{(aY - bY - lt / 2)}$$

ditional efficiency measures are reflected by the factor $f^{efficiencyMeasure}$ with the use of waste heat as a typical example:

$$cf_e = \left(1 - f^{efficiencyMeasure}\right)$$

he described structure and setup of the model allow a flexible parameterization for different technical decarbonization options and external scenario assumptions and subsequently the generation of automated simulation runs.

2.2. Model validation

In this section, the validation of the bottom-up model is presented, whereby the validation, as well as modeling of future transformation paths, described in the section 2.3, is exemplarily performed on the German glass industry using the years 2017 to 2019. Since they account for 80 % of German glass production and are responsible for about 77 % of the CO_2 emissions emitted by the German glass industry, only the container and flat glass industries are considered in this study [12,16]. First, direct CO_2 emissions recorded at the German Emissions and

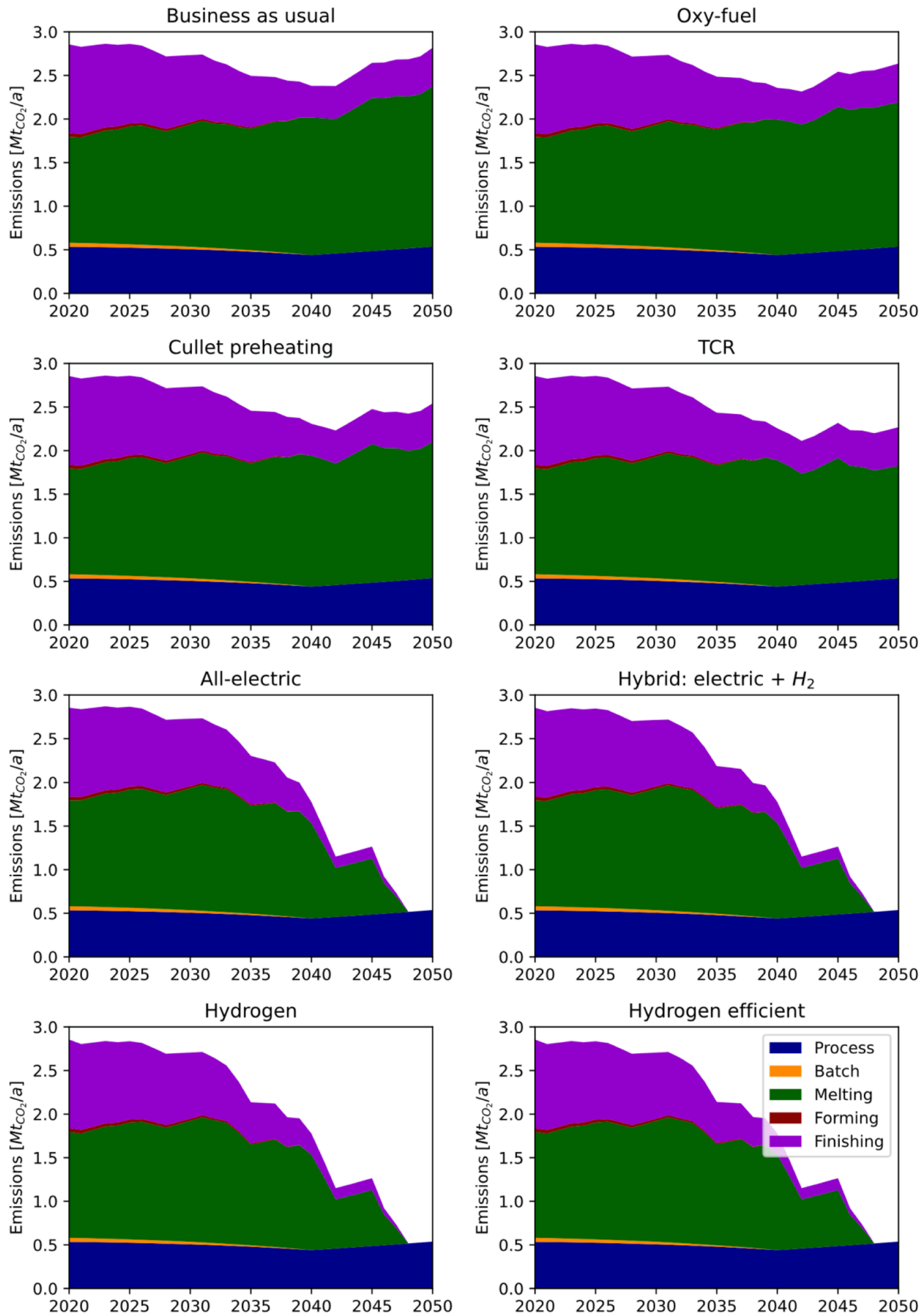

Fig. 10. CO_2 emissions of the German flat glass industry by process step for different technical scenarios while considering the extreme scenario assumptions regarding CAGR, investment periods and energy supply (cf. Table D2).

Trading Authority (DEHSt) were reconciled with those simulated by the model. Second, calculated glass production volumes (glass packed) were compared with the data compiled by the Federal Association of the German Glass Industry (BV Glas).

Direct CO_2 emissions include the sum of CO_2 emissions caused by the combustion of carbon-containing fuels and process-related CO_2 emissions. As described in Section 2.1, fossil fuel demand is assumed to consist of 100 % natural gas, with a CO_2 emission factor of 0.06 $t_{CO2}/GJ_{Natural\ Gas}$ [27]. Process-related CO_2 emissions are determined using the raw material-based emission factors and the cullet share dependent on glass type and glass color listed in Table G4 (minimum values).

The comparison of **calculated direct CO_2 emissions and CO_2 emissions recorded at the DEHSt** of the container and flat glass industries is shown production site-wise for the years 2017 to 2019 in Fig. 2 and Fig. 3. If several melting furnaces at one production site are listed individually at DEHSt, the data and calculations were aggregated. Fig. 2 indicates that the modeled container glass CO_2 emissions slightly underestimate the measured emissions. For 2019, the slope of the linear regression model is closer to the optimal slope than for 2017 and 2018. The mean deviation of total CO_2 emissions over the entire validation period is 10 %. For flat glass, it can be seen in Fig. 3 that the modeled emissions of smaller production sites overestimate measured emissions.

Table 3
Determination of minimum and maximum CO_2 budgets for the entire German glass industry as well as the German container and flat glass industry.

	Strict Budget (1.5 °C based)	Loose Budget (2 °C based)	Start date	Unit	Source
Global CO_2 budget	420	1170	01/01/2018	Gt_{CO2}	[4]
Share German population	1.1		–	%	[34]
CO_2 share industry	20	25	–	%	[35]
CO_2 share glass industry	3	4	–	%	[21]
CO_2 budget glass industry	17.7	112.0	01/01/2020	Mt_{CO2}	–
CO_2 share container/ flat glass industry	40	40	–	%	[21]
CO_2 budget German container/ flat glass industry	7.1	44.8	01/01/2020	Mt_{CO2}	–

In 2017 and 2018, the modeled emissions slightly underestimate measured emissions of bigger production sites. Based on the available data, the deviations cannot be clearly explained. The reasons can be manifold, e.g., varying utilization rates, deviating quality requirements evoking respective retention times or installed efficiency boosters such as cullet preheaters. Table C1 lists the deviations between calculated and measured direct CO_2 emissions, where the deviations are aggregated values of the container and flat glass industry which were weighted by melting capacites. In the period from 2017 to 2019, the computed results show average deviations of about 20 and 25 % for the container and flat glass industries.

The **distributions of specific CO_2 emissions** and the **specific combustion-related energy consumption** of the melting furnaces are presented in Fig. 4 and Fig. 5. Specific process emissions of container glass vary with the corresponding glass color (cf. Table G4) between 0.01 and 0.09 t_{CO2}/t_{Glass}, which is in the range of the mean value for German container glass (0.09 t_{CO2}/t_{Glass}). Specific process emissions of flat glass are constant at a value of 0.19 t_{CO2}/t_{Glass}, which corresponds exactly to the mean value for German flat glass [28]. For container glass, both *SEC* and direct combustion-related CO_2 emissions are subject to fluctuations. In addition to different cullet rates, this is mainly due to different furnaces types and their size and age. Extreme upward outliers are furnaces that produce relatively small amounts of pharma & cosmetics glass. The mean value calculated in 2019 for fossil combustion-related emissions for the melting process of 0.23 t_{CO2}/t_{Glass} only slightly underestimates the mean value for the German container glass industry of 0.255 t_{CO2}/t_{Glass}. Furthermore, the calculated mean value for *SEC* in 2019 of 4.64 GJ/t_{Glass} is almost identical to the value of 4.68 GJ/t_{Glass} determined by Fleischmann et al. [29]. For flat glass, *SEC* values and direct combustion-related CO_2 emissions fluctuate due to furnace capacity and furnace age. The outlier at the bottom represents a furnace for patterned glass. The mean value computed for 2019 for fossil combustion-related emissions in the melting process of 0.37 t_{CO2}/t_{Glass} matches the mean value for the German flat glass industry. In addition, the calculated mean value for *SEC* in 2019 of 6.58 GJ/t_{Glass} meets the value of 6.55 GJ/t_{Glass} given by Fleischmann et al. [29].

The **glass production quantities** stated by BVGlas are given as glass packed. Therefore, the pull rates of glass melt determined for furnaces must be corrected by the pack-to-melt ratio. For container and flat glass, pack-to-melt ratios of 0.9 and 0.83 were assumed [22]. Table C2 shows the deviations between calculated and given glass packed quantities. In the period from 2017 to 2019, the production quantity deviations amount to an average of 18 and 10 %, respectively.

2.3. Transformation pathways

This section explains the technical transformation pathways for the German glass industry and presents the selection of external parameters, also referred to as scenario assumptions. Technical efficiency measures are modeled for melting furnaces only. Brief descriptions of the characteristics of the German glass industry, decarbonization options for the glass industry, and the input data used for modeling is provided in the

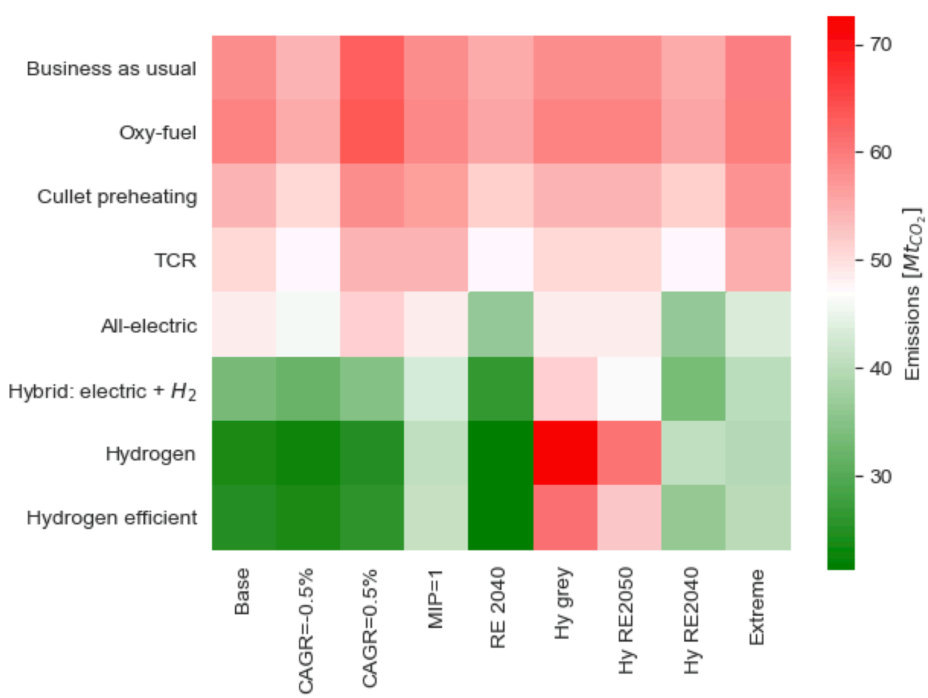

Fig. 11. Cumulated CO_2 emissions of the German container glass industry for different technical scenarios while varying CAGR, investment periods and CO_2 intensity of energy supply for the period from 2020 to 2050 (cf. Table D1).

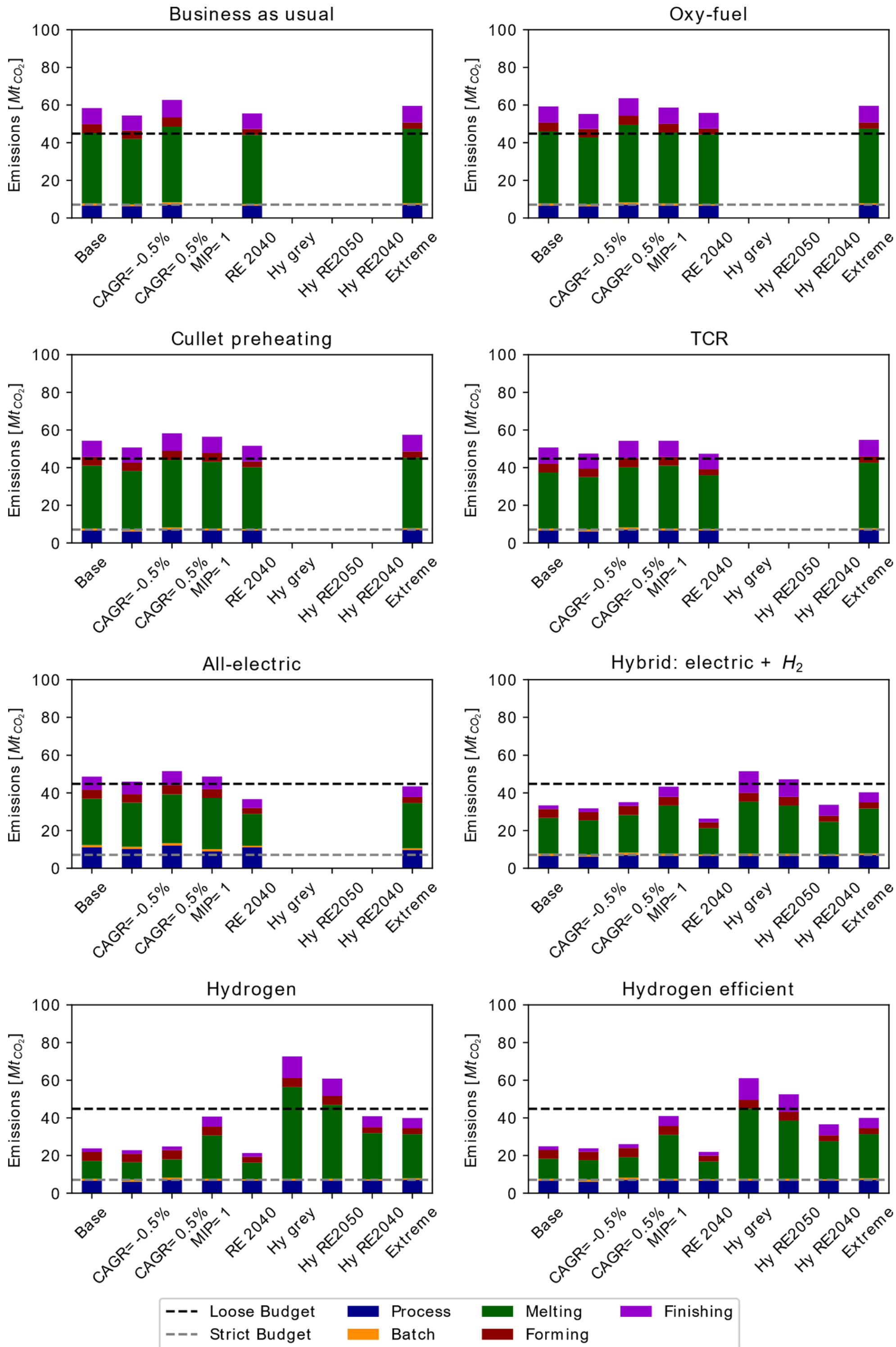

Fig. 12. Cumulated CO_2 emissions of the German container glass industry by process step for different technical scenarios while varying CAGR, investment periods and CO_2 intensity of energy supply for the period from 2020 to 2050 (cf. Table D1).

Appendix F-H. All other process steps change exclusively due to fuel switching or parameter changes, e.g., compound annual growth rate (CAGR) or CO_2 intensity of energy carrier.

The basis of the technical transformation pathways is the construction of mortality lines for each existing melting furnace, accounting for the existing lifetime and the lifetime resulting from the technical change (see Table G3). Each technical scenario assumes that all existing melting furnaces are replaced by the same technical decarbonization option. As shown in Table 1, technical decarbonization option means either one or several combined technical changes. In the future, a range of options will most likely emerge depending on different techno-economic boundary conditions, but the extreme considerations allow clear conclusions on the extent to which a corresponding option reduces CO_2.

The business as usual case is considered as the benchmark, which continues the operation of existing plants. Thermo-chemical heat recovery (TCR) uses oxygen as an oxidizer in combination with heat

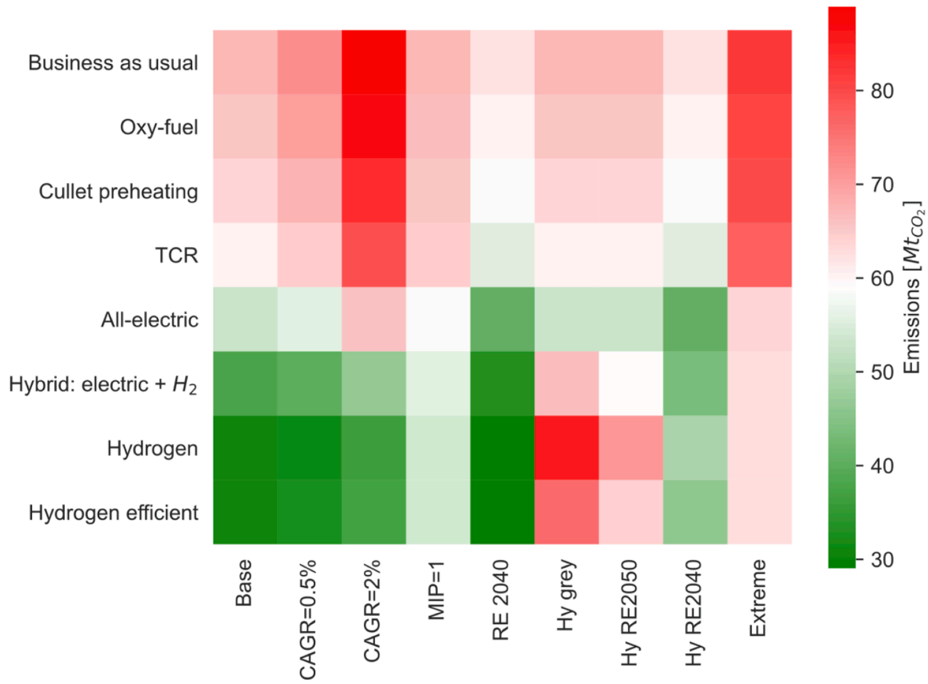

Fig. 13. Cumulated CO_2 emissions of the German flat glass industry for different technical scenarios while varying CAGR, investment periods and CO_2 intensity of energy supply for the period from 2020 to 2050 (cf. Table D2).

recovery, providing an efficiency improvement of 30 %. All-electric melting replaces conventional melting furnaces with cold-top electric furnaces, whereby the maximum cullet content for this melting technology is 55 %. Due to limited data availability, the all-electric *SEC* for flat glass was estimated based on the ratio of all-electric and side-port fired container glass furnaces. For the post-forming and finishing process, the all-electric option assumes that gaseous energy demand is met with the same electrical energy quantity since possible efficiency improvements cannot be quantified accurately. The hydrogen option substitutes the fossil natural gas assuming the same specific energy consumption. Since energy efficiency will play a more important role in future energy systems, also due to increasing energy prices, a hydrogen efficient scenario is also defined. The 30 % efficiency improvement is a conservative estimate based on a combined use of oxy-fuel combustion (10 %) and regenerative checkers as well as cullet preheating (together 20 %) for heat recovery. First hybrid melting systems enabling flexible operation of hydrogen combustion together with high shares of electricity are commercially available allowing electric energy shares between 20 and 80 % [30]. With a maximum electrical *SEC* share of 80 %, the maximum allowable cullet rate is 90 %. In this study, the distribution of energy carriers for the hybrid melting system is assumed to be constant at 70 % electricity and 30 % hydrogen and the cullet share is not further constrained.

External parameters regarding the development of CO_2 emissions are the development of the compound annual growth rate (CAGR), in this case the glass production quantity, and the CO_2 intensity of utilized energy carriers.

The historical data on the CAGR development of the German container and flat glass industries shown in Fig. C1 illustrate a slight downward and a moderate upward trend, respectively. In addition, Fig. C1 demonstrates that demand developments can fluctuate strongly in the course of unforeseeable events such as economic crises. In contrast to the container glass industry, the flat glass industry is very export-driven [31]. On average, the container and flat glass industries show CAGRs of −0.5 and 2 % respectively in the period from 2005 to 2019. The study “Climate Paths for Germany” [32] which aims to identify macroeconomically cost-effective ways of achieving Germany's emission reduction targets estimates an annual demand increase of 0.5 % for the entire industrial sector. Therefore, as shown in Table 2, the CAGR is varied in this study between −0.5 and 0.5 % and 0 and 2 % for the container and flat glass industries, respectively.

To assess the impact of missed investment decisions of a certain decarbonization option in terms of cumulative CO_2 emissions, the parameter missed investment period (MIP) is introduced. If no investment decision is missed (MIP = 0), existing melting furnaces will be replaced at the end of their lifetime by a melting system which employs the corresponding decarbonization option. If the first investment decision (MIP = 1) is missed, old melting furnaces will be substituted with equivalent new ones. After completing this investment period, the corresponding decarbonization options will be implemented. The defined external scenario assumptions are given in Table D1 and Table D2.

Historical CO_2 emission factors for the German electricity grid and postulated CO_2 emission factors of different energy carriers are shown in Fig. 6. The development on the CO_2 intensity of the German electricity mix shows a significant reduction of almost 50 % from 1990 to 2019, highlighting a clear downward trend. To continue this trend, based on the 2020 electricity mix, it is assumed that the share of renewable energy is 100 % in 2050 (RE 2050) or 2040 (RE 2040), with linear interpolation in the intermediate years. A constant emission factor is applied for gas. In case of hydrogen usage, only the emissions occurring during production are considered. In addition to green and grey hydrogen, the electrolysis production is examined with the previously assumed development of the German electricity mix, considering a LHV based efficiency of 70 %.

3. Results & discussion

This section first presents and analyzes the effects of different technical decarbonization options in terms of CO_2 emissions for the container and flat glass industries. Subsequently, the influence of the external parameters compound annual growth rate (CAGR), missed investment period (MIP), electricity mix and the mode of hydrogen production towards cumulated CO_2 emissions is investigated via a sensitivity analysis.

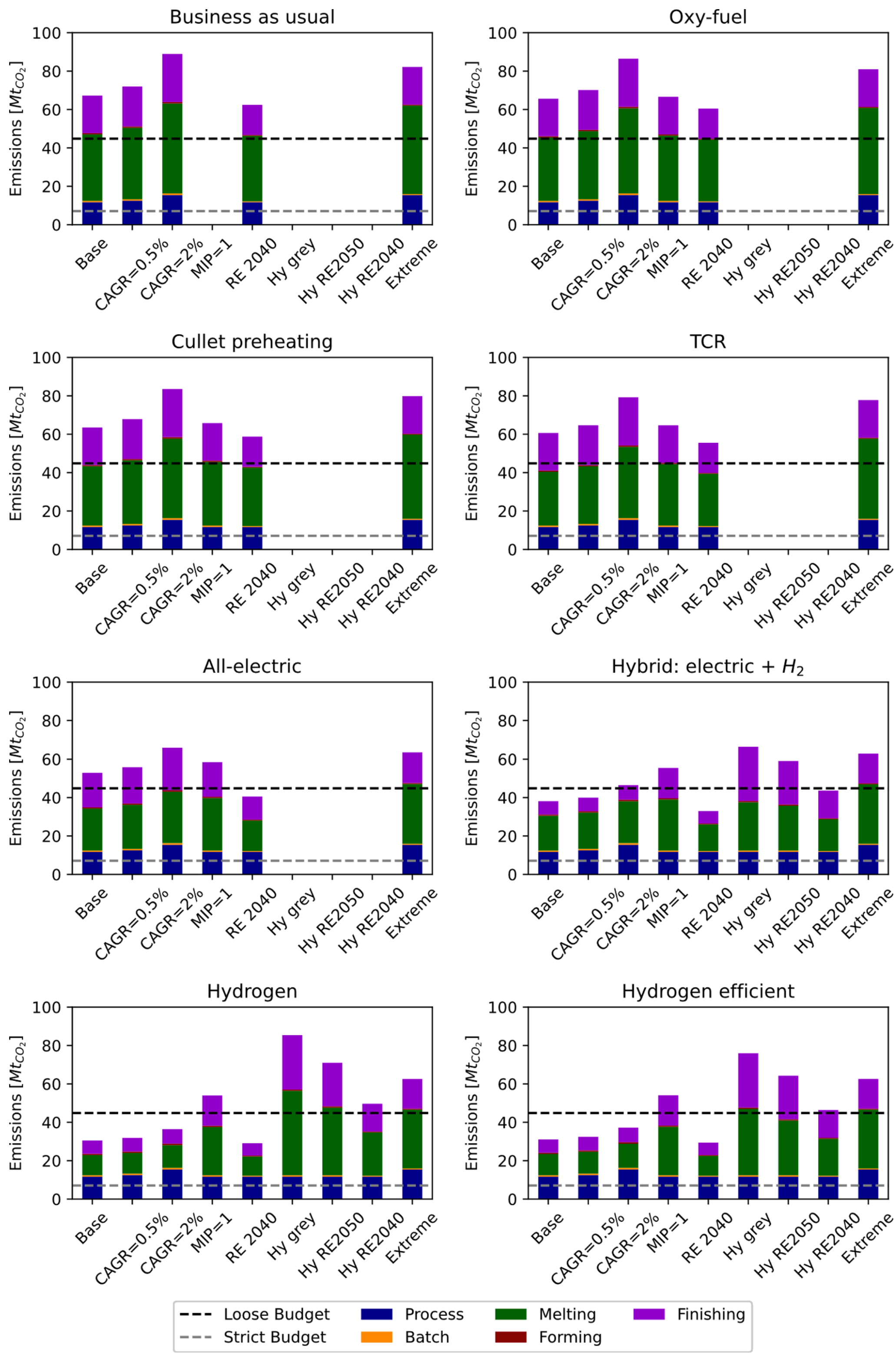

Fig. 14. Cumulated CO_2 emissions of the German flat glass industry by process step for different technical scenarios while varying CAGR, investment periods and CO_2 intensity of energy supply for the period from 2020 to 2050 (cf. Table D2).

3.1. Development of carbon dioxide emissions

For the container glass and flat glass industries, the results are discussed in the following using the base and extreme scenarios as examples (cf. Table D1 and Table D2).

While Fig. 7 compares the CO_2 emissions of different technical decarbonization options for the entire container glass production line, Fig. 8 illustrates the distribution of emissions within the entire production line for each individual decarbonization option.

It can be observed that, in descending order, melting and fining, forming as well as post-forming and finishing contribute to the evoked CO_2 emissions. For all options, even the business as usual case, CO_2

Table A1
Furnace database attributes from [26].

Furnace database
Company
City
Furnace type
Furnace capacity
Construction year
Glass type
Glass category
Glass color

Table A2
Database attributes of the German Emissions and Trading Authority (DEHSt).

DEHSt database
Company
Plant name
State
City
CO_2 equivalents for different years

emissions decrease over the considered period. The upper left graph in Fig. 8 shows that the emission reductions of the business as usual case are on the one hand due to slightly reduced process emissions in correlation with the marginal increase in cullet shares. On the other hand, the decrease in the CO_2 intensity of the electricity mix leads to a partial (melting and fining, post-forming and finishing) or complete (batch preparation, forming) reduction of indirect electricity-related emissions in each process step. The non-linear progression of CO_2 emissions in the melting process for the business as usual case can be explained by the construction of new melting furnaces whose energy consumption has not yet increased due to aging effects. For the discussed decarbonization options, this effect is superimposed with the corresponding efficiency improvement and / or the change in CO_2 intensity of the energy carrier. Since the CO_2 intensity of green hydrogen was assumed to be constant at zero throughout the whole time frame, the explained non-linearities are therefore most clearly observed for hydrogen-based options. Taking the hydrogen and hydrogen efficient options as an example, it can be clearly seen that, assuming the lifetimes shown in Table G3, all existing furnaces can be replaced by alternative (e.g., hydrogen-based) systems by 2032. In the remaining period from 2032 to 2050, a linear decreasing trajectory is perceptible due to the decline in the CO_2 intensity of the electricity mix, until in 2050 only process-related emissions are recorded (cf. Fig. 7 and Fig. 8 Hydrogen and Hydrogen efficient).

When comparing the hydrogen and hydrogen efficient options, the slightly increased CO_2 emissions of the hydrogen efficient option can be attributed to the electricity-related oxygen production. Since green hydrogen is considered, efficiency improvements that result in reductions of hydrogen consumption do not lead to further reductions of CO_2 emissions. The situation changes in case hydrogen is produced via CO_2 intensive energy carriers. The most significant negative slopes occur between the years 2026 and 2027 because no data on the year of construction was available for 32 % of all considered 56 container glass furnaces and thus the years of construction for regenerative and recuperative furnaces were set to 2014 for these cases. This assumes that melting furnaces with missing construction year data will have reached their mean lifetime in 2020, the beginning of the scenario time frame. For the all-electric decarbonization option, the initial period till 2032 shows that CO_2 emissions are higher than for the business as usual case, as the CO_2 intensity of the electricity mix outweighs the gained efficiency improvement. From 2038 on, the all-electric option emits less CO_2 than the TCR technology. The moderately increased process emissions result from the maximum cullet rate of 55 %, which is technically required for all-electric melting. The hybrid melting system providing process heat via electricity and hydrogen is not limited in terms of cullets. For all options, the remaining CO_2 emissions in 2050 consist only of process emissions. CO_2 reductions of the natural gas-based efficiency improving options oxy-fuel, cullet preheating, and TCR follow the level of efficiency improvement, with oxy-fuel and TCR superimposed by the electricity consumption of oxygen supply. Observing the business-as-usual and oxy-fuel options, the two curves intersect several times due to different electricity and gas requirements and different lifetimes. The business as usual option emitting less CO_2 at the early part of the study period and the oxy-fuel option emitting less CO_2 in 2050.

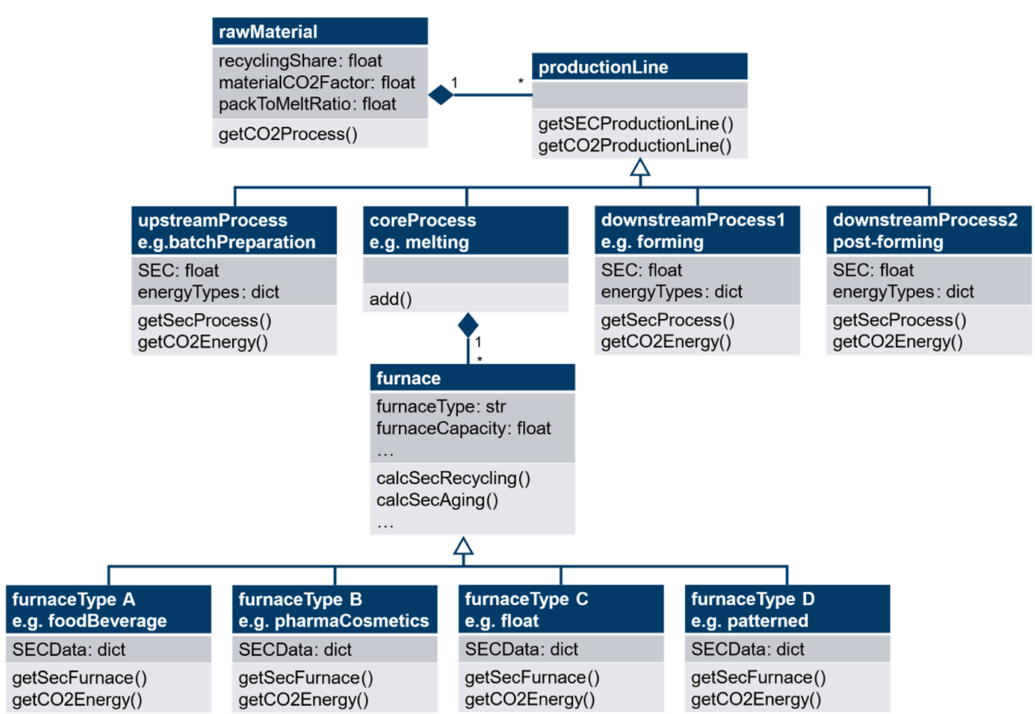

Fig. B1. Class diagram of the bottom-up model for the production line of an energy-intensive process.

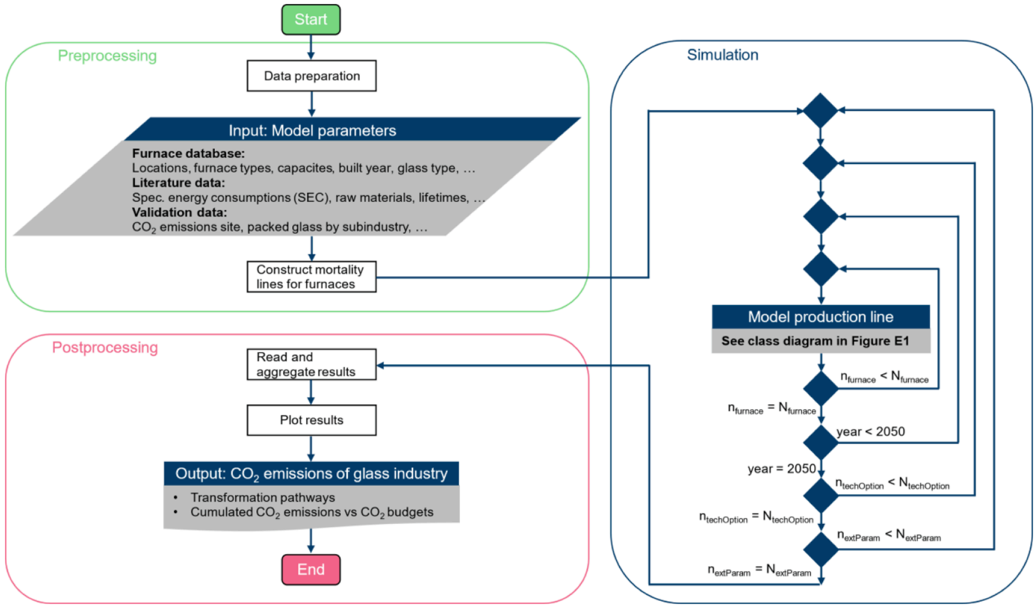

Fig. B2. Flowchart of the simulations including preprocessing and postprocessing.

Table C1
Deviations between modeled direct CO_2 emissions and those recorded by DEHSt (weighted by pull rate).

	2017	2018	2019	Mean
Container	19 %	20 %	17 %	19 %
Flat	25 %	23 %	29 %	26 %

Table C2
Deviations between modeled glass packed quantities and those recorded by BVGlas. For container and flat glass, a pack-to-melt ratio of 90 and 83% respectively was assumed.

	2017	2018	2019	Mean
Container	17 %	18 %	19 %	18 %
Flat	10 %	5 %	15 %	10 %

As previously described, the trajectory of CO_2 emissions for flat glass results from the assumptions CAGR = 2 %, MIP = 1, 100 % renewable electricity by 2040, and green hydrogen. Fig. 9 compares the CO_2 emissions of different technical decarbonization options for the entire flat glass process and Fig. 10 depicts the distribution of emissions of the glass production process for each individual decarbonization option. Due to missing investments in the initial phase, no deviations of the different considered decarbonization options are observed until 2031. The replacement of the conventional technologies occurs in the period between 2031 and 2048, when the last furnaces are phased out. For flat glass, CO_2 emissions of batch preparation and forming are negligible. The business as usual case illustrates that the highest emissions are consistently due to melting and fining. Initially, more CO_2 emissions are caused by post-forming and finishing than by process-related emissions, but this changes over time due to the decrease in CO_2 intensity of the electricity mix. Unlike container glass, absolute process-related emissions are identical for all options, since, first, there is no differentiation of the cullet share based on the glass color and, second, there exist no process-related limitations for all-electric melting (maximum cullet share 50 %). The 2 % annual increment in assumed cullet share has a greater effect than the annual increase in production quantity (CAGR = 2 %) until the maximum cullet share is reached in 2040. After that, process emissions increase due to CAGR. The natural gas-based options exhibit the same performance as those for container glass, with the exception that the gap between business as usual and oxy-fuel is much clearer and the two corresponding curves do not intersect. This is due to the different underlying assumptions for oxy-fuel efficiency improvements. For flat glass, a 10 % improvement was assumed. For container glass, the values shown in Fig. G1 were used. The divergence between the decarbonization options hydrogen and hydrogen efficient is negligible from a CO_2 point of view for the whole period since the first investment period has been missed and the electricity mix will be CO_2 neutral in 2040. Due to the development of the German electricity mix, the all-electric flat glass option shown in Fig. 9 indicates significantly steeper decreases than the all-electric container glass option presented in Fig. 7.

3.2. Cumulative emissions in the context of sectoral budgets

To assess the simulation results of the different considered scenarios, the definition of CO_2 budgets for the German container and flat glass industry is indispensable.

Global CO_2 budgets are linked to global warming targets. However, formulations of CO_2 budgets are associated with strong uncertainties. Hence in this paper, as shown in Table 3, bandwidths (strict and loose budget values) are used to formulate CO_2 budgets for the German glass industry.

Global 67th percentiles for the 1.5 °C and 2 °C target values are 420 and 1170 Gt_{CO2} from January 2018 on [4]. Using the German share in total world population of 1.1 %, a German CO_2 budget can be allocated [34]. After subtracting the total German emissions for 2018 and 2019 of 856 and 810 Mt_{CO2}, and accounting for the CO_2 based glass industry emission share, the remaining strict and loose budgets from 2020 on are 17.7 and 112 Mt_{CO2}, respectively. If the container and flat glass industries are each assumed to contribute 40 % of the emissions caused by the glass industry, this results in CO_2 budget targets of approximately 7 and 45 Mt_{CO2}, respectively, which must be achieved or undershot.

Fig. 11 and Fig. 12 present the results of the sensitivity analysis for the container glass industry. The sensitivity analysis for the container glass industry indicates that no combination of technical decarbonization option and assumed scenario meets the strict 1.5 °C based CO_2 budget target. Achieving this target, even under the hypothetical assumption of immediate available green hydrogen, would require additional reduced process emissions and / or the use of CO_2 separation

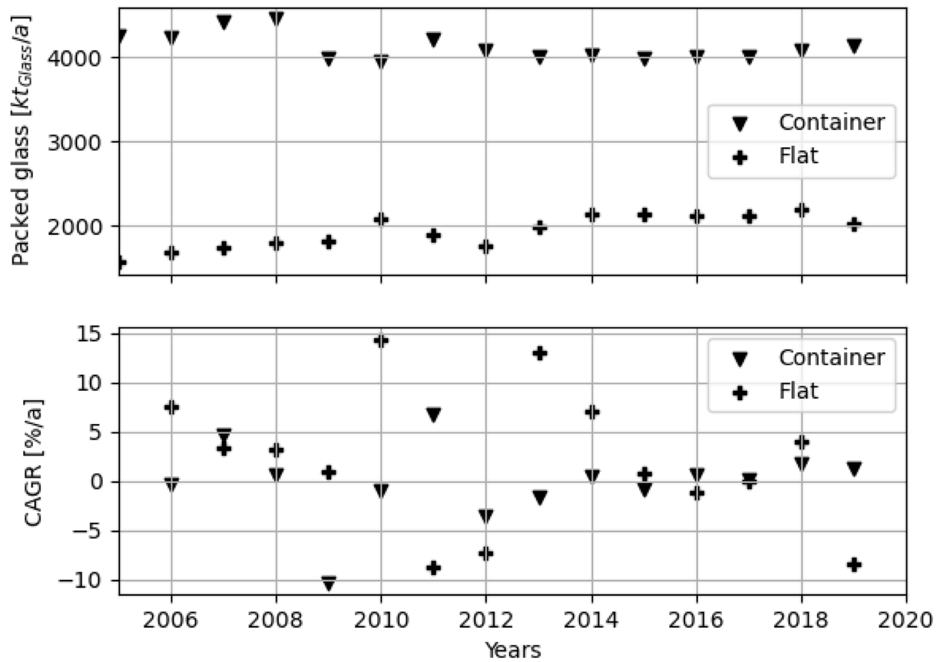

Fig. C1. Historic development of produced glass and compound annual growth rate (CAGR) for the German container and flat glass industries (data from).

Table D1
Scenario assumptions for the container glass sector. RE 2050 and RE 2040: 100% share of renewable energy in 2050 and 2040, with linear interpolation starting from 2020.

ID	Name	CAGR	MIP	Electricity	Hydrogen
1	Base	0 %	0	RE 2050	Green
2	CAGR −0.5 %	−0.5 %	0	RE 2050	Green
3	CAGR 0.5 %	0.5 %	0	RE 2050	Green
4	MIP 1	0 %	1	RE 2050	Green
5	RE 2040	0 %	0	RE 2040	Green
6	Hy grey	0 %	0	RE 2050	Grey
7	Hy RE2050	0 %	0	RE2050	Hy RE2050
8	Hy RE2040	0 %	0	RE 2040	Hy RE2040
9	Extreme	0.5 %	1	RE 2040	Green

Table D2
Scenario assumptions for the flat glass sector. RE 2050 and RE 2040: 100% share of renewable energy in 2050 and 2040, with linear interpolation starting from 2020.

ID	Name	CAGR	MIP	Electricity	Hydrogen
1	Base	0 %	0	RE 2050	Green
2	CAGR 0.5 %	0.5 %	0	RE 2050	Green
3	CAGR 2 %	2 %	0	RE 2050	Green
4	MIP 1	0 %	1	RE 2050	Green
5	RE 2040	0 %	0	RE 2040	Green
6	Hy grey	0 %	0	RE 2050	Grey
7	Hy RE2050	0 %	0	RE2050	Hy RE2050
8	Hy RE2040	0 %	0	RE 2040	Hy RE2040
9	Extreme	2 %	1	RE 2040	Green

technologies, e.g., carbon capture and storage (CCS), carbon capture and utilization (CCU) or direct air capture (DAC).

All four investigated natural gas-only based options (business as usual, oxy-fuel, cullet preheating and TCR) fail to achieve the mild target linked to the 2 °C goal in every conceivable scenario. Due to additional electricity demand, the oxy-fuel option does not reveal significant improvements over the business as usual option. The TCR-based options are much closer to the loose target but, if at all, qualify as a bridge technology or would need to be combined with the CO_2 separation

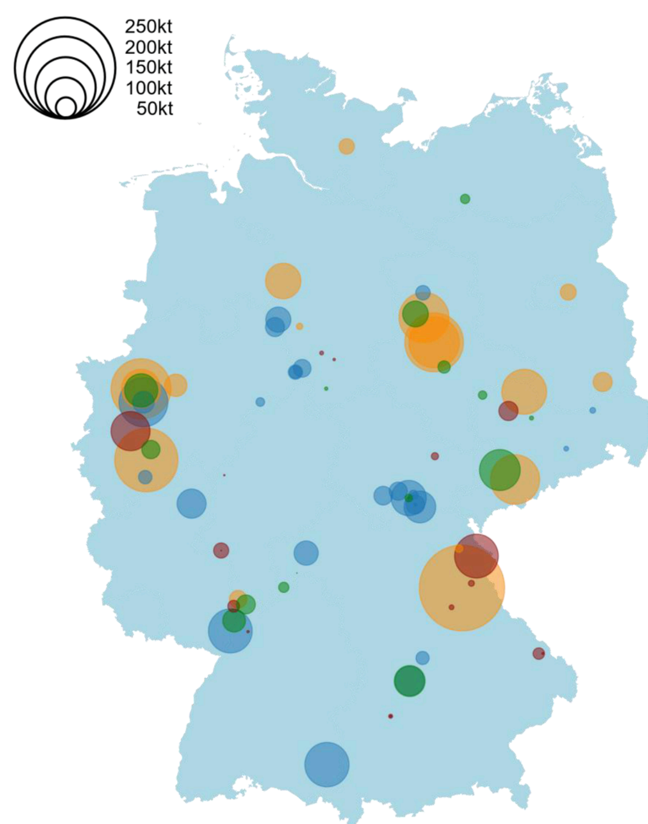

Fig. E1. Local distribution and absolute CO_2 emissions of glass companies in Germany. The colors indicate the different glass industry segments: Container glass (blue), flat glass (orange), glass fibers (green) and special glass (red) (based on [21]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

technologies. Except for the RE 2040 scenario, all scenarios for all-electric melting are non-compliant with the loose CO_2 budget target, even if some of them exceed it only minimally. Besides the CO_2 intensity

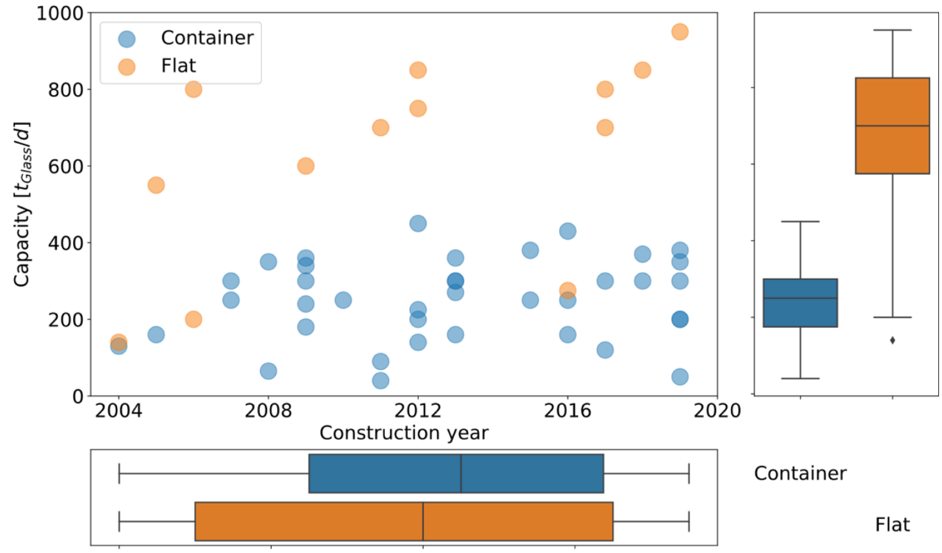

Fig. E2. Furnace capacities und furnace construction years for German container and flat glass industries.

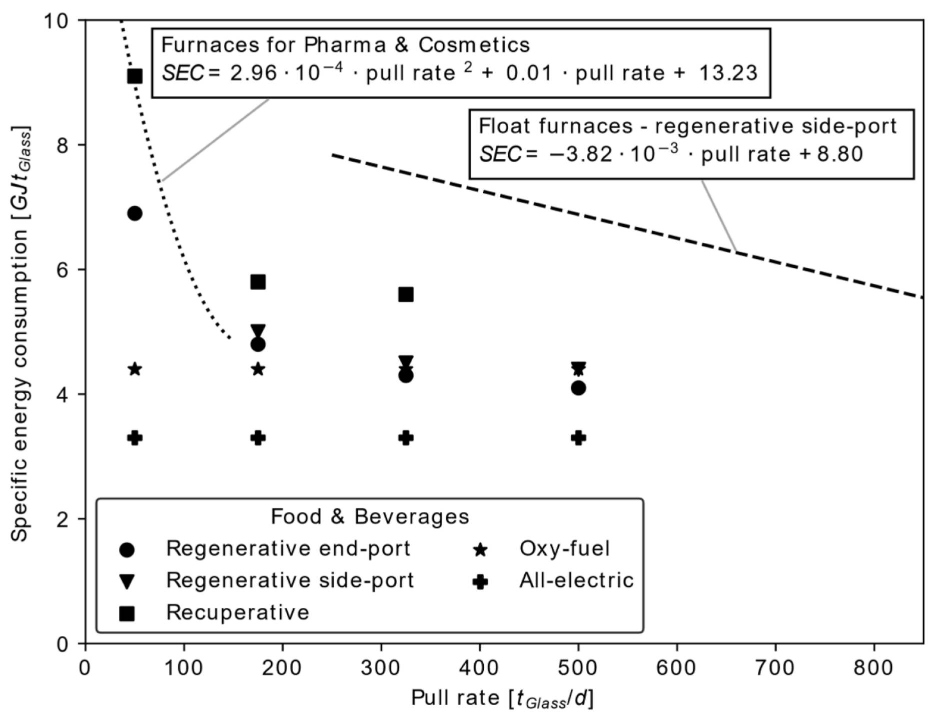

Fig. G1. Specific energy consumption (*SEC*) of container and flat glass furnaces during the melting and fining process normalized on cullet share measured at half of the lifetime (data from [24,25]).

of the German electricity mix, the missed CO_2 reduction targets are to a weaker extent due to slightly increased process emissions resulting from the technical limitation of the cullet share. The hydrogen-based decarbonization options offer the strongest CO_2 reductions. However, the sensitivities with respect to hydrogen supply highlight the imperative requirement for hydrogen production to be as CO_2-neutral as possible. Due to the even higher CO_2 footprint of grey hydrogen compared to natural gas (both constant over time), hydrogen options with grey hydrogen are even more CO_2 intensive than the natural gas-based options. Therefore, the efficiency improvements of the hydrogen efficient option have a particularly significant effect for grey hydrogen (as well as for the RE Hy2050 scenario). In addition, the more efficient supply of energy will play an increasingly important role due to rising energy prices. Whereby, rising energy prices are either a consequence of switching from fossil natural gas to more expensive renewable energy carriers or, if fossil fuels are retained, increasing CO_2 prices. Simulating the miss of the first investment opportunity for the green hydrogen-based options, the results for the container glass industry show that the loose CO_2 budget target can still be met but the cumulative amount of CO_2 almost doubles. The hybrid option of electricity and hydrogen smoothes out the previously described results in the form that the cumulative CO_2 emissions increase and decrease slightly for green and grey hydrogen supply, respectively. As shown in Fig. 6, the CO_2 intensity of grey hydrogen, is lower than that of the German electricity mix until 2028, but is then increasingly undercut in the subsequent years until 2050.

Table F1
Advantages and disadvantages of selected decarbonization options.

Decarbonization Option	Advantage	Disadvantage
Oxy-fuel	Efficiency (o) Applicable to renewables, e.g. H_2	Oxygen
Cullet / batch preheating	Efficiency (+) Applicable to renewables, e.g. H_2 Periphery change	Additional process
Thermo-chemical heat recovery (TCR)	Efficiency (++)	Further use of natural gas
All-electric melting (EM)	Efficiency (++)	CO_2 intensity electricity mix Energy supply / security
Hydrogen	Energy supply / security CO_2 intensity of renewable H_2	CO_2 intensity of other H_2
Recycling of cullets	Efficiency (+) Process emissions	Limited availability Limited cullet share for EM

Table G1
Specific energy consumption (*SEC*) for container and flat glass in the process steps batch preparation, forming and post-forming and finishing (based on [11,16]).

	Container Glass		Flat Glass	
GJ/t_{Glass}	Electricity	Fuel	Electricity	Fuel
Batch preparation	0.15	–	0.15	–
Forming	0.60	–	0.13	–
Post-forming and finishing	0.13	0.90	2.43	1.43

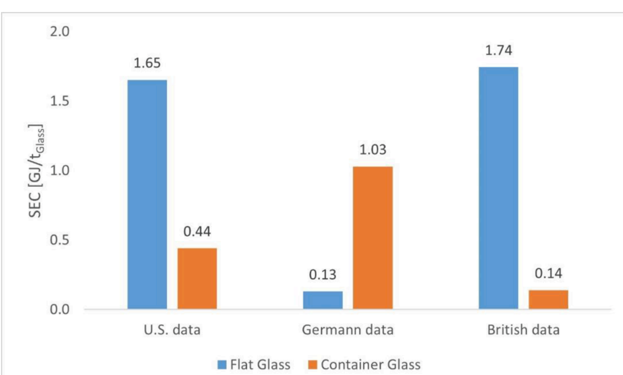

Fig. H1. Electric specific energy consumption (*SEC*) for the **forming** process of container and flat glass in different countries (data from [11,16,34]).

Fig. 13 and Fig. 14 display the results of the sensitivity analysis for the flat glass industry. It is also evident for the flat glass industry that none of the simulated combinations can ensure conformity with the strict CO_2 budget targets. The level of cumulative CO_2 emissions for flat glass industry is higher than for container glass. Furthermore, the distribution of the emissions to the individual processes is clearly different. For the flat glass industry, the emissions from post-forming and finishing and higher process emissions are particularly significant. The post-forming and finishing process even represents the highest proportion of emissions for the purely hydrogen-based technical options. Due to the high electricity content of the finishing process in the flat glass industry, hydrogen-based options cannot reduce CO_2 emissions to the same extent as in the container glass industry. In contrast to the container glass industry, the emissions caused by the forming process are negligible for the flat glass industry. For both container and flat glass industries, the

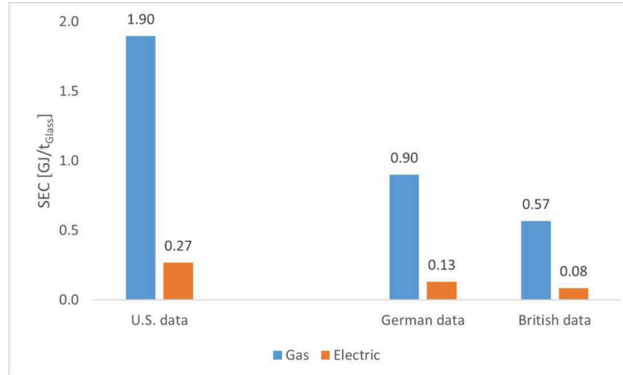

Fig. H2. Specific energy consumption (*SEC*) for the **post-forming and finishing** of **container** glass in different countries (data from [11,16,34]).

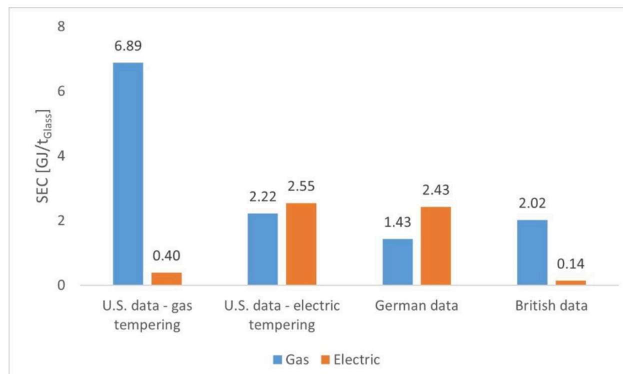

Fig. H3. Specific energy consumption (*SEC*) for the **post-forming and finishing** of **flat** glass in different countries (data from [11,16,34]).

Table G2
Assumptions for modeling specific energy consumption (*SEC*) of container and flat glass furnaces during the melting and fining process.

	Container Glass		Flat Glass	
Glass category	Food & Beverages	Pharma & Cosmetics	Float	Patterned
Utilization furnace	90 %		80 %	
Melting & Fining	f (pull rate, furnace type)	f (pull rate)	f (pull rate)	5.58 (air-reg.) 4.36 (oxy-fuel)
Energy carrier(s) specified in source	Fossil	Fossil + electricity	Fossil	Fossil
Cullet share specified in source	50 %	50 %	25 %	–
Aging	2.4 %/a			
Electric boosting share	7.5 %			
Source	[41]	[41]	[42]	[29]

Table G3
Assumed lifetimes of different glass melting furnaces (data from [41]).

Furnace type	Container	Flat
Regenerative	12	14
Recuperative	12	14
Oxy-fuel	10	
Cold-top electric melter	6	
Hybrid melter	10	

Table G4
Assumed cullet shares for different glass types and glass colors. Process-related emissions are based on raw material emissions of 193 and 208 $kg_{CO2}/\ t_{RM}$ for container and flat glass, respectively (data from [10,16,44]).

Glass color	Cullet share min [wt%]	Cullet share max [wt%]	Process-related CO_2 emissions min [kg_{CO2}/t_{Glass}]	Process-related CO_2 emissions max [kg_{CO2}/t_{Glass}]
Container				
Green	80	90	38.6	19.3
Brown	70	80	57.9	38.6
White	60	70	77.2	57.9
Flat				
–	10	50	187.2	104

CO_2 emissions caused by melting and fining vary similarly with the assumed technical decarbonization option and the emissions during batch preparation are negligible. The magnitude of the CAGR plays a more signifcant role for both the container glass industry (variation between −0.5 and 0.5 %) and the flat glass industry (variation between 0 and 2 %) for those options that do not or only slightly reduce CO_2 emissions. Considering missing the first investment opportunity for the green hydrogen-based options, the results for the flat glass industry show that this leads to failing the loose CO_2 budget targets. In contrast to the container glass industry, the results of the hybrid electric and hydrogen option are much more diverse. Not only the Hy grey and Hy RE2050 scenarios cannot achieve the loose CO_2 budget target, but also four others (CAGR = 0.5 %, CAGR = 2 %, MIP = 1, Extreme). The Extreme scenario was introduced to show the superposition of maximum CAGR, a missed investment decision, and a 100 % renewable electricity mix by 2040. For container glass, the hydrogen-based options can meet the loose CO_2 budget targets even for the extreme scenario, but this is not the case for flat glass.

4. Conclusion

Based on in-depth knowledge, a bottom-up model was developed to accurately predict the future CO_2 emissions of an energy-intensive industrial sector. Using the German container and flat glass industries as an example, the effects of various technical decarbonization options and external scenario assumptions were analyzed. The model was validated using site-specific CO_2 emissions and sector-wide glass production quantities. Since the lifetime of existing melting furnaces is considered on a site-specific basis, the influence of missed alternative investment decisions can be evaluated.

The simulation results for the time frame from 2020 to 2050 show that no modeled combination of decarbonization option and scenario is compatible with the 1.5 °C based strict CO_2 budget target, but all significantly exceed it. The 2 °C based loose CO_2 budget target is only achievable via a fuel switch, i.e., the complete phase-out from natural gas to renewable energies such as green hydrogen or electricity from wind power or photovoltaics. Therefore, the results show once again that political decision-makers must create framework conditions to maximize the expansion of renewable energies as fast as possible.

Green hydrogen exhibits the highest CO_2 reduction potentials, while the all-electric option significantly depends on the temporal evolution of the electricity mix. The faster achievement of a CO_2 neutral electricity mix reveals significant improvements towards the CO_2 budget. Green certificates or power purchase agreements (PPAs) may help companies to improve their carbon footprint. Especially the sensitivities of different hydrogen production types show a strong impact towards the CO_2 budget. Serious targeting of the 1.5 °C target means that the reduction of process-related CO_2 emissions will gain in significance. It remains to be seen whether the cullet share will be further increased, alternative raw materials such as hydroxides instead of carbonates be used, or CO_2 separation technologies applied.

Finally, techno-economic considerations concerning the glass production process, e.g., efficiency, CAPEX, OPEX, flexibility of operation, technology readiness level (TRL), together with the aspect of energy availability and the political framework conditions will decide in each individual case when which production facility will initiate the fuel switch and whether process-related costs will also have to be significantly reduced.

CRediT authorship contribution statement

Michael Zier: Conceptualization, Data curation, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization. **Noah Pflugradt:** Supervision, Writing – review & editing, Project administration. **Peter Stenzel:** Supervision, Writing – review & editing, Project administration. **Leander Kotzur:** Supervision, Writing – review & editing, Project administration. **Detlef Stolten:** Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgements

The authors would like to thank the German Federal Ministry of Education and Research (BMBF) for funding provided within the “Kopernikus - Power-to-X” project. Furthermore, the authors would like to express their gratitude to Mr. Bernhard Fleischmann of the “Hüttentechnische Vereinigung der Deutschen Glasindustrie e. V.” (HVG) and the “Deutsche Glastechnische Gesellschaft e.V.” (DGG) for answering questions, constructive discussions and proofreading of this paper.

Appendix A. Data attributes

Table A1 and Table A2 show the important attributes of the furnace database and the input data of the German Emissions and Trading Authority (DEHSt).

Appendix B. Class diagram and flow chart of the bottom-up model

Figs. B1 and B2.

Appendix C. Validation results

Tables C1 and C2.

Figs. C1.

Appendix D. Scenario assumptions

Tables D1 and D2.

Appendix E. Characteristics of the German glass industry

Germany is the largest European glass producer with an annual production quantity of 7.4 Mt in 2019, which corresponds to about 20 % of the packed glass in Europe [12,13]. Europe, along with North America and China, is one of the largest glass producers in the world, producing around 36 Mt per year (as of 2019) [36]. The total fuel consumption of the German glass industry is approximately 70 PJ, with natural gas, electricity and oil accounting for about 75 %, 20 % and 5 %, respectively [14,15]. The total German direct (process emissions and emissions from the combustion of fossil fuels) CO_2 emissions in 2019 were 4 Mt [21]. The container and flat glass industries each have CO_2 emission shares of 40 % and 37 %, accounting in total for 77 % of the glass industry's emissions [21]. The remaining CO_2 emissions are attributable to the specialty glass and mineral fiber industries.

Fig. E1 shows the local distribution of German glass companies. Absolute CO_2 emissions are indicated by size. The affiliation to the corresponding glass industry sector is highlighted by color. The major CO_2 point sources are flat glass sites, which almost exclusively operate air regenerative side port-fired float furnaces with large capacities of about 700 t_{Glass}/d and require relatively high specific energy consumption. Smaller container glass furnaces are distributed over several smaller sites, whereby air regenerative end-port fired furnaces being used in most cases with usual melting capacities in the range of 250 t_{Glass}/d [26].

In 2019, a total of 77 facilities subject to emissions trading were recorded, including 70 glass production facilities and seven mineral fiber production facilities. The distribution of furnace capacities and years of construction for container and flat glass furnaces is shown in Fig. E2.

Appendix F. Decarbonization options for the glass industry

Since a large part of the CO_2 emissions in the glass industry is caused by the combustion of fossil fuels in glass melting furnaces, energy efficiency measures as well as fuel switching towards renewable energy carriers are logical solutions. Therefore, the most important energy measures and fuel switching options, both overarchingly denoted (energy-related) decarbonization options, are shortly presented to provide the technical foundation for the transformation pathways that will are constructed in Section 2.3. Key advantages and disadvantages are outlined in Table F1. For a detailed analysis of different decarbonization options, refer to [28].

Oxy-fuel furnaces burn the fuel with purified oxygen (>92 vol%) [37]. With the reduction of the nitrogen share, the gas flow through the furnace drastically decreases, leading to an efficiency enhancement of approximately 10 % in comparison to air regenerative furnaces [19,20]. Electricity is utilized for the purification of oxygen. Therefore, the electricity mix of the considered country is decisive for the reduction of CO_2 emissions.

In conventional air regenerative furnaces, the combustion air is preheated, with hot flue gases leaving the regenerators at temperature of approximately 500 °C. Using the remaining waste heat of the hot flue gases leaving the regenerators to **preheat cullet and batch** material, reduces fuel consumption by about 15 %, but may pose operational challenges [21,22].

Thermo-chemical heat recovery (TCR) combines oxy-fuel combustion with a heat recovery process. Thereby, natural gas is blended with about 20 % of the recirculated hot flue gas (mainly H_2O and CO_2) to reform the gas. This produces a hot synthesis gas consisting mainly of hydrogen and carbon monoxide, while increasing the lower heating value (LHV) [38].

All-**electric melting (EM)** using submerged electrodes significantly improves the efficiency of energy input into the glass melt. However, the efficiency improvement decreases with increasing melting capacity, since the efficiency of fired melting furnaces increases stronger with increasing capacitythan the efficiency of all-electric furnaces. Due to a completely different process as compared to combustion, a large number of changed operating conditions have to be taken into account, e.g., pull rate flexibility, limited cullet share or lower furnace lifetimes. A limited melting capacity of approximately 250 t_{Glass}/d may be overcome by modular approaches [[39]].

Among alternative renewable energy carriers for combustion, **hydrogen** is the most promising, as the main competitors biogas and synthetic methane, will either be limited in availability or will have additional exergy losses and higher costs [28]].

Recycling of cullets accelerates the melting process, saves energy and reduces energy-related emissions. An increase of 10 % recycled cullets by weight leads to an improved energy efficiency of approximately 2.5 %. In addition, process-related emissions are reduced because cullets do not release CO_2 when melted.

Appendix G. Detailed description of the input data

The bottom-up model was developed based on a furnace database [26] and literature data, e.g. specific energy consumption (*SEC*), raw material composition or average melting capacity utilization.

The balance boundary covers the entire production line, with specific LHV-based energy consumption values recorded for each process step. In addition, process emissions are captured. Since the natural gas share of fossil fuels used in the German glass industry is greater than 90 %, only natural gas is considered as a fossil combustion fuel.

If no data is available on the year of construction of a discrete furnace, it is assumed that the furnace will have reached half of its lifetime in 2020. Based on the input data, CO_2 emissions can be determined location-wise. The model was validated using metrics from the years 2017 to 2019 such as product quantity [40] and direct CO_2 emissions [21]. Subsequently, different technical decarbonization options were simulated while accounting for more general external scenario assumptions, e.g., compound annual growth rate (CAGR) or CO_2 intensities of different energy carriers to investigate their impacts on future total CO_2 emissions of the container and flat glass industries.

Specific energy consumptions (SECs) of **batch preparation, forming** as well as **post-forming and finishing** are assumed constant (Table G1), where SECs are average figures for the respective glass sectors. Therefore, values may deviate significantly in individual cases. In batch preparation and forming processes, only electricity is used as an energy carrier, with the share of total energy consumption being marginal in both cases. Among the process steps shown in Table 2, the largest energy consumption occurs in post-forming and finishing, comparatively lower for container glass and higher for flat glass. Reports from different industrialized countries show that specific energy consumptions of the forming process vary widely (cf.

Fig. H1). Depending on the product requirements, different processes such as annealing, coating, tempering, or laminating are employed in the post-forming and finishing part, which can vary significantly in terms of energy consumption and utilized energy carrier. Also, for the post-forming and finishing process, the *SEC* can vary significantly (cf. Fig. H2 and Fig. H3).

Table G2 and Fig. G1 provide information on how ***SEC*** is determined with respect to the **melting and fining** process. Container glass was divided into the subgroups food and beverages as well as pharmaceuticals and cosmetics and flat glass into float and patterned glass. Nominal melting capacities are retrieved from the furnace database. The correlation to the glass pull rate is established via an average utilization factor. For container and flat glass, utilization factors of 90 and 80 % respectively were assumed [37]. Depending on the data availability, *SEC* was determined using a discrete (food and beverages – discrete values in Fig. G1) or continuous (pharmaceuticals and cosmetics, float – continuous functions in Fig. G1) dependence on the pull rate, or the *SEC* was set constant (patterned). Except for pharma and cosmetic glass, where the *SEC* corresponds to the sum of fossil fuels and electric power, the *SEC* figures of the other glass types refer exclusively to fossil fuels, which is assumed to be natural gas. As shown in Fig. G1, the *SEC* data for food and beverages glass distinguishes between a range of melting furnace types. The *SEC* data points exhibit on oxy-fuel and electric furnace exhibit no dependence on the pull rate. When using oxy-fuel furnaces, the electricity required for oxygen supply is rated at a specific energy consumption of 0.3 GJ/t_{Glass} [41]. The *SEC* curve for pharma and cosmetic glass consists of aggregated data for regenerative and recuperative furnaces, highlighting the severe dependence of *SEC* within small pull rate ranges. For both container and flat glass, it is assumed that the share of electrical boosting equates to 7.5 % of total energy consumption. This is an adequate assumption because 75 % of German container glass furnaces use electric boosting, contributing on average to 10 % of total energy consumption [37]. Due to unavailability of data, the share of electric boosting of the container glass industry was adopted for the flat glass industry. The *SEC* figures are normalized to the cullet share, which are given in Table G2.

For the given SECs, it is assumed that they are average values measured at half of the melting furnace lifetimes. High-temperature applications are subject to aging effects, which are considered for the melting furnaces with an annual increase in energy consumption of 2.4 %. With a lifetime of 12 years, this corresponds to a difference in energy consumption of 33 %. Supposed lifetimes of considered melting furnaces are listed in Table G3.

The **lifetimes** of conventionally fired melting furnaces (regenerative, recuperative, oxy-fuel) show values in the range of 10 to 14 years. All-electric cold-top furnaces have drastically lower lifetimes because of their significantly reduced volume, which results in severe convection currents that cause a lot of stress on the furnace wall material [43].

As shown in Table G4, assumed **cullet shares** depend on the glass type, i.e., container or flat glass. In the case of container glass, the cullet share is further differentiated regarding the glass color.

The normalized *SEC* values given in Fig. G1 are denormalized using the following formula:

$$SEC = SEC_{Norm} \cdot \left(1 + \frac{(culletshare_{Norm} - culletshare) \cdot 2.5\%}{10}\right)$$

nimum cullet share values are assumed for years less than or equal to 2020 while maximum cullet shares are potential future upper bound values, assuming a possible annual cullet share increase of 2 percentage points. In case all-electric melting is employed, the maximum cullet share is set to 55 % due to process-related limitations of the cold-top furnace [45].

Appendix H.

Average *SEC* for Different Processes in Different Countries.

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