Beyond basic material production: The feasibility of CO_2-neutral process heat generation in Germany's industry

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Abstract

Deep decarbonisation of the European industry by 2050 requires action in all stages of manufacturing. Many publications focus on a few selected highly energy intensive basic materials such as high value chemicals, steel or primary aluminum. However, around half of the energy consumption for industrial process heating in the EU27 and the majority of installations and companies is outside these main processes.

Here, we conduct a broad analysis of the opportunities to switch to CO_2-neutral process heating for 34 applications across all energy-intensive subsectors but focusing processes so far less-investigated. In total these processes account for a third of industrial process heat use in Germany. We assess the technical maturity, energy efficiency and economics of CO_2-neutral process heat generation and compare it to the fossil-based status-quo. We create a set of techno-economic data of conventional and new technologies and model their competition and resulting diffusion under transformative economic conditions. The data set describes Germany but the concept and insights can be relevant for the entire EU27.

We find that some of these often overlooked applications have access to the necessary technologies which, with medium- to high-ambition economic measures, can be economically competitive. In particular, about 55 % (78 TWh) of the investigated energy demand, primarily consisting of steam generation and glass production, can decarbonize by 2040 or are close to it – given the ambitious measures applied in this analysis. Another 2 % (2 TWh) in highly specialized applications (hardening, carburizing, heat treatment of copper) lack economically attractive options in 2040. About 43 % (60 TWh) have economically attractive options available, but are unable to implement them fast enough to reach decarbonisation by 2040 or 2050. This group, challenged by long lifetimes of installations, mainly consists of steel processing and clinker production. For them, early price signals can support the transition. We conclude though, that some applications might require regulatory law, as even strong price signals do not sufficiently incentivize decarbonisation.

Introduction

With the goal of the European Commission to reach carbon neutrality by 2050, the industry sector faces challenges that encompass entire value chains, a huge variety of greenhouse gas (GHG) emission sources and technical, economic and societal aspects. One central challenge is the GHG-neutral generation of process heat. It combines the availability of specific and in some cases merely emerging technologies, their economic competitiveness compared to fossil fuels and the distinct task of deploying them in time.

The potential for GHG-emission reduction from process heat generation is usually investigated from either of two perspectives: a process-based approach or a sectoral approach.

- In the former, processes are described in high technological detail but the scope is limited to individual processes or small groups. Examples include (Cuviella-Suárez et al. 2021) who quantify the energy efficiency potential in a sanitary-ware (ceramics) factory, using a thermo-physical simulation. Similarly, (Dolianitis et al. 2016) simulate bath-preheating systems in container glass production, (Frassine et al. 2016) investigate energy efficiency options for glass melting furnaces with a database of European production sites and (Schmitz et al. 2021) show the technical options to replace natural-gas fired reheating furnaces in steel processing. (Fleiter et al. 2012) assess energy efficiency potentials in the German pulp and paper industry. (An et al. 2018) focus on economic indicators by applying an optimization model to several iron and steel production routes and (Arens et al. 2017) describe energy efficiency pathways in the iron and steel production of Germany. Recently, these technology- or process- specific analyses also focus the use of hydrogen, e.g. (Neuwirth et al. 2022). The main goals of such approaches are findings about the technological potential and feasibility of specific saving options. Depending on the degree of economic considerations, some of the studies describe potential diffusion pathways for the selected processes.

- Sectoral approaches on the other hand try to explain the energy demand of an entire sector and necessarily reduce complexity of the individual processes or sub sectors included. They acknowledge the high heterogeneity of activities in question (Napp et al. 2014; Fais et al. 2016) and thus typically focus on the processes with high energy intensity, especially iron and steel, cement and basic chemicals (Aden 2018; Bataille et al. 2018). The higher level of abstraction applied to the processes within the sector is thought to have limited impact on the results. The results obtained from these approaches can be linked more directly to possible transformation pathways and policy recommendations (Rissman et al. 2020).

Considering these existing analyses, we observe two gaps: First, it seems widely agreed-upon that energy and material efficiency are necessary tools for successful decarbonisation. They are though not sufficient to reach it (among others (Aden 2018; Allwood et al. 2010; Lechtenböhmer et al. 2016)) but require additional measures, in particular a switch to low-carbon energy carriers. The fuel switch potential and what conditions facilitate it, is however still in discussion.

Second, we identify a gap between highly detailed technological process-simulation and sector-wide techno-economic analyses. The most conclusive evidence for this may be that the latter focus on a limited number of processes with the highest energy demand but must neglect or abstract others that may make up more than 40 % of industrial energy demand (Allwood et al. 2010). These processes often include further processing of basic materials, e.g. by subsuming it with its production (like steel reheating furnaces in iron/steel production). Within these sums, their specific challenges and properties can be concealed by the energy-intensive processes.

In this contribution, we try to address both observed gaps. First, we assume a meso-perspective between process-specific and sectoral analyses with the definition of "applications"[1]. They group processes with similar properties and thus make them, by reducing their heterogeneity, accessible to model-based analysis. Second, we extend the scope of the analysis beyond the production of selected basic materials (Table 1).

Overall, we analyse the 34 applications given in Table 1. They range from steam use in chemicals, paper and food industries over foundries for ferrous and non-ferrous metals and reheating/heat treatment of steel products to glass melting, lime, cement, bricks and ceramics production. We combine the newly generated collection of technological data on these applications with an economic model that calculates economic attractiveness and resulting market diffusion of CO_2-neutral technologies by 2050. Based on their performance in a given scenario (consisting of price and policy assumptions), we identify challenges and suggest additional policies to contribute to climate targets. With this, we address the question, what conditions propel transformation of industrial process heat generation.

Methods and Data

This analysis is conducted as a two-part effort. First, we define "applications", which consist of one or more individual production steps for a given product and represent the most relevant process-heat use. We then gather techno-economic data for currently used and potential future climate friendly process-heat technologies. Second, we integrate the techno-economic data into a modeling frame to calculate cost competitiveness of new investments and compare the resulting market shares under varying external conditions. For this purpose, a model is used, which bases the attractiveness of the competing technologies on their heat generation costs.

The analysis follows a scenario-approach and is as such merely a small segment of the possible solution space. This applies to the techno-economic data of the technologies but to a larger degree the economic framework conditions. Developments may differ strongly depending on energy carrier price paths, policy decisions or market dynamics. The purpose of the analysis is thus not to make a prediction but to derive a plausible "if-then"-statement. The model approach allows quick and easy variations of several important assumptions and data sets, of which just one can be presented here. For this purpose, a scenario has been constructed based on a relevant previous publication and policy discussions in Germany (Fraunhofer ISI 2021a). Among others, the main impacts on the attractiveness of the available technologies and thus on the results stem from four factors: energy carrier prices, GHG-pricing, the decision rationale of the market participants and applied policy measures. The assumptions for those are presented in the following section.

MODEL STRUCTURE

The model builds upon the techno-economic data of the applications and technologies and adds to that information concerning the market environment and policy assumptions (Figure 1). With these, it calculates the attractiveness of available technologies within each of the investigated applications. This attractiveness is mainly influenced by the heat generation costs, consisting of the annuity of the investment, the cost of energy carriers, non-energy related operational expenditures (OPEX) and costs for GHG if applicable. The replacement of

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[1] The definition of these applications follows a qualitative literature research on economic and technological relevance. A detailed insight in the rationale leading to the selection and aggregation to applications will be given in the project report.

Table 1. Estimate of coverage of sectoral energy demand of investigated applications.

Attributed activity in energy balance	#	Application	Estimated production 2020[1] in kt	Estimated # of installations	Specific energy demand [GJ/t]	Estimated energy demand [TWh]	Fuel demand of the activity 2019[2] [TWh]	Share covered by analysis	Considered technologies[3]	Group allocation (see Figure 3)
Food industry	1	Milk powder production[4]	1609	10	3.6	1.6	36	4%	5	A
Paper industry	2	Paper drying	31371	93	2.6	22.7	32	71%	5	A
Chemical industry	3	Steam supply chemical park	40389	11	3.5	39.1	85	46%	5	A
Heat treatment (part of "iron and steel")	4	Continuous heating flat/long steel	33516	26	1.4	13.1	127	15%	4	D
	5	Continuous heat treatment flat steel	6907	14	1.0	1.9			3	D
	6	Discontinuous heat treatment flat steel	16116	1,700	0.8	3.5			3	D
(Non-ferrous metals) and foundries	7	Continuous melting cast iron (low capacity)	1000	2	3.3	0.9	14	43%	5	B
	8	Continuous melting cast iron (medium capacity)	500	5	3.0	0.4			5	B
	9	Continuous melting cast iron (high capacity)	600	29	3.1	0.5			5	B
Non-ferrous metals (and foundries)	10	Continuous melting aluminum	700	36	2.7	0.5			3	D
	11	Discontinuous melting/holding semi-finished casting aluminum	3319	74	2.9	2.7			3	B
	12	Continuous homogenizing/heating aluminum strip/profiles	1126	70	0.7	0.2			3	D
	13	Discontinuous homogenizing/heating aluminum strip/profiles	1862	103	0.6	0.3			3	D
	14	Continuous heat treatment aluminum strip	171	9	0.9	0.0			3	D
	15	Continuous melting copper continuous cast wire rod	592	1	1.0	0.2			3	D
	16	Continuous heating semi-finished copper products for hot forming (low capacity)	333	42	0.7	0.1			3	C
	17	Continuous heating semi-finished copper product for hot forming (high capacity)	416	1	0.8	0.1			3	C
	18	Discontinuous heat treatment copper semi-finished product (low capacity)	202	29	0.3	0.0			3	D
	19	Discontinuous heat treatment copper semi-finished product (high) capacity)	289	7	0.8	0.1			3	C
Metal processing	20	Continuous heating of forged components	186	4	1.7	0.1	12	21%	4	B
	21	Discontinuous heating of forged components	306	26	2.5	0.2			3	D
	22	Continuous heating of steel sheet blanks	240	8	1.4	0.1			3	B
	23	Continuous heat treatment (service)[5]	531	82	1.5	0.2			4	C
	24	Continuous heat treatment (in-house)[5]	2125	81	2.1	1.2			3	C
	25	Discontinuous heat treatment[5]	1148	707	2.0	0.6			3	C
Glass and ceramics	26	Continuous melting container glass	3368	47	4.5	4.2	18	86%	5	A
	27	Continuous melting flat glass	2444	12	7.7	5.2			5	A
	28	Continuous burning bricks	9306	370	1.9	4.9			3	D
	29	Continuous burning refractory bricks	600	24	5.5	0.9			3	D
	30	Discontinuous burning refractory bricks	150	19	5.8	0.2			3	D
Processing of non-metallic minerals	31	Continuous burning lime (low reactivity)	1476	43	4.6	1.9	47	72%	4	D
	32	Continuous burning lime (medium/high reactivity)	2284	23	3.9	2.5			3	D
	33	Continuous burning lime (high throughput)	858	4	5.7	1.4			5	D
	34	Continuous burning cement clinker	25310	39	4.0	28.1			5	D
		SUM		3,751		**140**	**371**	**38%**	**126**	

1. Estimated from installed capacity and average capacity utilization - both researched in this project.

2: According to national energy balance Germany (AGEB e. V. 2020).

3. Basic technology types are: fossil reference (often natural gas-fired, in specific cases fuel mixes), direct electrification, CO_2-neutral fuels (hydrogen or synthetic hydrocarbons) and biomass. Versions of (partial) direct electrification and hydrogen are present as option for all applications.

4. Milk powder has been selected as exemplary case for steam demand in food processing. For food, paper and chemical industry, the unit of activity refers to steam production.

5. Carburisation and austenitisation.

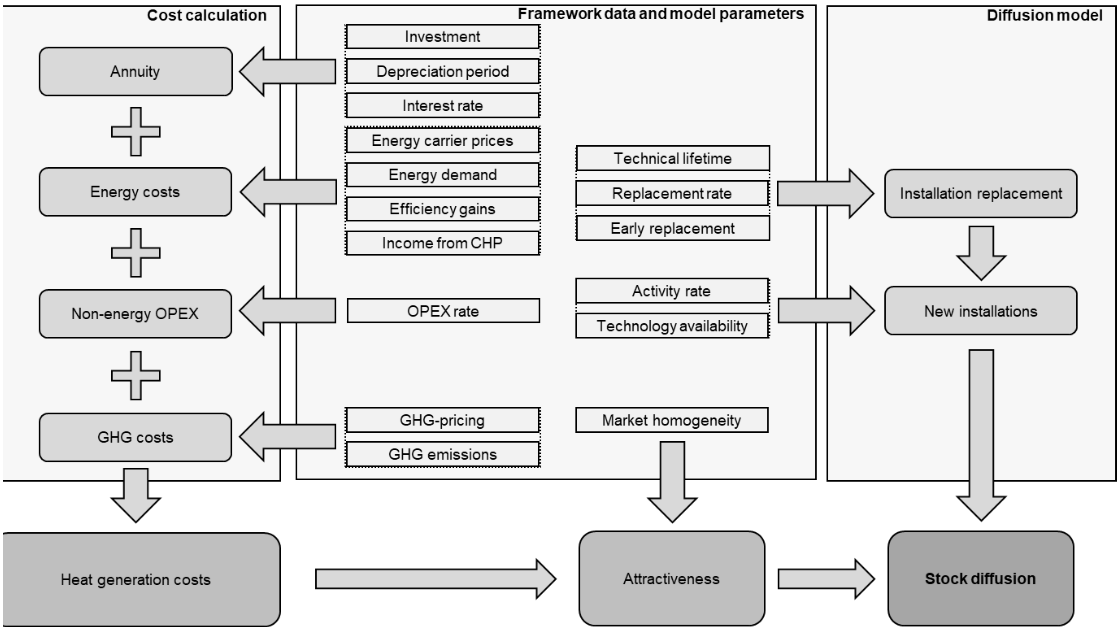

Figure 1. Model workflow and parameters.

installations is a function of attractiveness, replacement rate and installed capacity[2].

RESULT SOLUTION SPACE

The main result of the model is the diffusion of CO_2-neutral technologies by application, measured as share of production output (e.g. "*the process heat for 35 % of paper drying is supplied with new technologies such as heat pumps or electrode boilers*"). This diffusion is limited by two factors (Figure 2). First, the economic attractiveness of new installations (which can reach at most 100 %), directly resulting from the heat generation costs in competition with other technologies. Equal heat generation costs create equal attractiveness. High attractiveness means that old installations are more likely to be replaced with this technology – whenever they are replaced.

Second, the actual implementation of this attractiveness by the replacement of installations (which can at most be as high as the attractiveness), the diffusion limit. Whenever the decision to replace an existing installation is made, there is a chance – governed by the technology's attractiveness – that this specific technology is installed. Assuming a static case, in which the attractiveness never changes, we expect the share of this technology on the total stock of installations narrowing down on this attractiveness (either growing or shrinking towards it). In decarbonisation scenarios, we additionally expect that alternative (low CO_2 or CO_2-neutral) technologies grow and fossil decline, if the scenario conditions are constantly improving for the former[3].Simply put, the actual diffusion of a given technology always "trails behind" its attractiveness. Thus, if attractiveness keeps growing, the diffusion may never exceed it. This is the case in the scenario presented here, thus used to confine the solution space and represented by the diagonal line in (Figure 2). It is, however, not a property of the model but merely the scenario. In return, we would see all fossil technologies (not shown in this analysis), below the diagonal line in (Figure 2).

TECHNO-ECONOMIC DATA AND ASSUMPTIONS

The techno-economic data are the basis of the calculation. Main data points include the specific energy demand, the used energy carriers, efficiency potentials, representative capacity and process-related emissions on the technical side as well as investment, non-energy operational costs and depreciation period on the economic side (Table 2). Examples for specific applications are published in (IOB RWTH 2021). The collected data – both for the applications/technologies and for the external conditions, e.g. energy carrier prices –refer to Germany, but the insights can be relevant for a number of other countries. The following data points constitute an ambitious transformation scenario in which strong efforts lead to a decarbonized electricity generation and the availability of CO_2-neutral technologies. In addition, policy measures are implemented aimed at increasing the viability and attractiveness of decarbonized process heat generation, including policies that are not currently planned or for which detailed knowledge of the imple-

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[2] Additional descriptions and results for selected individual applications can be found in Rehfeldt et al. 2021a and Rehfeldt et al. 2021b. In these earlier publications (in German), individual applications are investigated in detail and are subject to staged and progressive changes of policy measures. In contrast, here, we show all applications incorporated in the model with a fixed policy and economic environment.

[3] I.e. the scenario creates a convex function of the attractiveness of alternative technologies. Any non-linearities, such as price shocks influencing the attractiveness on a small timescale, may create situations where the attractiveness of alternative installations is lower than their share in stock. Note that the diffusion limit is not an applications' or a technologies' fixed property or exogenous assumption, but a variable value, depending on its attractiveness.

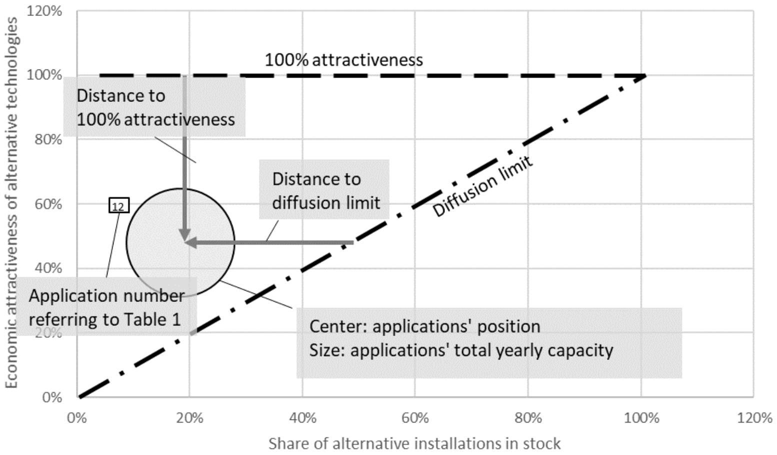

Figure 2. Diffusion results, explanatory figure. The size of the circles indicate (qualitatively) the production capacity (largest circle about 50 Mt) of the application. The abscissa shows the share of existing alternative technology installations in this application in 2040 and the ordinate the economic attractiveness of new alternative installations for this application.

Table 2. Example of techno-economic data set.

Application	Property	Reference	Alternative 1	Alternative 2	Unit[1]
Continuous heat treatment flat steel products	Name	Natural gas-fired[2]	Hydrogen-fired	Electric	-
	Product	Flat steel products			-
	Investment greenfield	190	190	152	€/tcap.
	Investment modernization	95	95	76	€/tcap.
	Minimum investment greenfield	190	190	152	€/tcap.
	Minimum investment modernization	95	95	76	€/tcap.
	TRL	9	< 4	< 4	-
	Energy carrier 1	Natural gas	Hydrogen	Electricity	-
	Energy carrier 2				-
	Energy carrier 3				-
	Specific energy demand 1	0.28	0.28	0.24	MWh/tpr.
	Specific energy demand 2				MWh/tpr.
	Specific energy demand 3				MWh/tpr.
	Minimum specific energy demand	0.25	0.25	0.21	MWh/tpr.
	Process-related emissions				tCO_2-eq./tpr.
	Operation and maintenance costs	11.40	11.40	11.40	€/tcap.
	Depreciation period	10.00	10.00	10.00	a
	Modernization cycle	35.00	35.00	35.00	a
	Representative capacity	530,000	530,000	530,000	tpa
	Average utilization	0.95	0.95	0.95	-
	Share of existing stock	100%	0%	0%	%
	Available from[3]	2020	2030	2030	-
	Available until	2050	2050	2050	-
	Total capacity application			7270.52	kt
	Internal electricity generation				MWhel/tpr.

1: "tcap." refers the respective value to installed capacity, "tpr." to metric ton of product. "tpa" is production per year in metric tons.

2: In the scenario presented here, no biogas or other CO_2-neutral gases are included. However, the methodology includes the possibility to adjust the emission factor (and/or prices) of the gas mix used for "natural gas" fired technologies to any path.

3: The availability depends on the technical readiness level TRL. For a TRL<3, the technology is assumed to be available from 2040. For a TRL<9 and ≥3, the technology is assumed to be available from 2030.

mentation is lacking – for example a reduction of components in the electricity price or an energy tax increase of natural gas.

The techno-economic data have been gathered for 34 different applications, each having (on average) three alternative technologies (Table 1) available to choose from. The data sets are based on literature research according to the state of the art supported by interviews with manufacturers, end-users and associations of the relevant German industry. The data sets show mostly average values. It must be noted that the data sets thus cannot represent individual installations.

Energy carrier prices

The relative prices of energy carriers have a strong impact on technology competition and are thus a highly relevant assumption. In the modelled scenario, most energy carrier prices are assumed to be constant (hard coal, waste, other fossils) or change just slightly (electricity, natural gas[4]) between 2020 and 2050. Merely fuel oil and biomass increase in price (Table 3)[5].

Table 3. Energy carrier prices assumptions.

Energy carrier	Unit	2020	2050
Electricity	€/MWh	88.54	92.52
Natural gas	€/MWh	27.40	26.53
Hard coal	€/MWh	15.44	15.44
Biomass	€/MWh	24.95	29.56
Fuel oil	€/MWh	49.50	69.26
Waste (renewable fraction)	€/MWh	15.08	15.08
Waste (non-renewable fraction)	€/MWh	7.70	7.70
Other fossil	€/MWh	19.80	19.80

GHG-pricing

The pricing of GHG-emissions is one of the central instruments of the European Union and national states to facilitate a transformation of the industry sector. In the last year, a strong increase of the certificate price in the EU-ETS has been observed, presumably as reaction to tightened climate goals and thus decreased emission caps[6]. In the model, several GHG-pricing paths can be applied, for the scenario and results presented here, the "high" path is used. Starting from €55/tCO_2-eq., it reaches €100/tCO_2-eq. by 2030 and increases by 100 every decade after that.

Decision rationale

In addition to the hard facts (or assumptions) on prices, a companies' decision to invest in new assets and technologies is influenced by perception, strategy and other factors that are sometimes intangible but in general less accessible to quantification. In this analysis, we implement the following three aspects of in the simulation algorithm that go beyond a pure cost-based assessment. First, we consider a price foresight of five years. This means that for investment decisions in e.g. 2032, the carbon and energy carrier prices of 2037 are used[7]. Second, we incorporate a measure of less tangible influences such as information access, called market homogeneity[8]. It influences the relevance of price differences between two technology options, with a high homogeneity favouring the cheapest/best one (with penny-switching 100 %-market shares as extreme solution), while a low homogeneity levels differences (with equal market shares as extreme solution). In this scenario, the market homogeneity is set to a comparably high value, which results in a market share of 66 % for a technology that is 10 % cheaper than its competitor (reaching 34 %)[9]. Third, we consider a replacement rate of existing installations. The basis for this value is the technical lifetime of the installations. It differs by equipment but ranges from 15 years (glass furnaces), with the majority around 25 years (e.g. heat treatment of steel products), to 40 years (melting furnaces for copper and cast iron)[10]. The replacement rate, assuming that the transformation towards sustainable production induces and requires higher dynamics, reduces these cycles. In the selected scenario, equipment may be reinvested already after it has reached 60 % of its technical lifetime. The average age of the installation stock thus decreases over time, e.g. from 15 years in 2020 to 9–11 years in 2040.

Policy measures

With rather constant (assumed) energy carrier prices, policy measures to influence the attractiveness of technologies, especially regarding electrification, are of high importance. GHG-pricing is one of them, but next to it, we consider three specific elements. First and foremost, removing the policy-related components of electricity prices, i.e. taxes and levies reduces the perceived electricity price to about 45 % of the values presented in Table 3. This price level is equivalent to the strongest relief currently in place for selected consumers in Germany (BDEW 2021). Second, the energy tax exemption on industrial uses of natural gas is removed, increasing the price of natural gas by €5.5/MWh. Third, the effective transmission of CO_2-pricing on the electricity price is limited to 30 % of the actual price increase. This effectively reduces the electricity price (compared to the data in Table 3) by about €20/MWh, with a diminishing return by 2040, as electricity generation is assumed to decarbonize by 2045[11].

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[4] EUROSTAT 2021a, 2021b.

[5] Note these are mere assumptions and not prescriptive or prognostic in any way. In fact, the developed model can be used to quickly and conveniently investigate the effects of a broad variety of energy carrier price assumptions and thus address the inherent uncertainty of them (and other assumptions).

[6] The model does not include an EU-ETS simulation. It just uses the CO_2-price as component for the cost of process heat generation. Mechanics of the EU-ETS such as free allocations are thus not represented.

[7] The foresight period is optional and variable between 0 and 20 years. The mechanic uses a perfect foresight, i.e. no uncertainty on the price signal is included.

[8] This is a concept to simulate the abstracted effect of information on decision processes, when limited empirical data is available (e.g. Fraunhofer ISI 2021b; Bataille et al. 2006).

[9] A moderate value would – with the same cost difference – yield a market share difference of 10 % (i.e. 55 % versus 45 %). These settings are assumptions as no empirical data is known to the authors on this technological level. On a higher level, concerning entire sectors, empirical values between 52 % and 55 % (note that these have not been represented in this format there) have been found in Rehfeldt et al. 2018. Values for transformative paths (e.g. the "high" setting) are assumptions.

[10] The data sets shows average values for examples of a specific application. The values of individual installations will vary.

[11] Emission factors for electricity generation are: 0.43 tCO_2-eq./MWh in 2020, 0.11 by 2030, 0.03 by 2040 and 0 by 2045.

Results

The investigated 34 applications align inside the created solution space (Figure 3), which represents the results for 2040 including all measures described above, i.e. in a scenario with strong transformation effort. Measured by the two factors (attractiveness and distance to the diffusion limit), some clusters can be identified. We categorize the applications in four groups. "Group A", with low distance to 100 % economic attractiveness and low distance to their current diffusion limit, dubbed "Advantaged". "Group B" with low distance to 100 % economic attractiveness but medium distance to their diffusion limit, dubbed "Boosted". "Group C", with medium to high distance to 100 % economic attractiveness but low distance to their diffusion limit, dubbed "Cornered". Finally, "Group D" with low to medium distance to 100 % attractiveness but high distance to their diffusion limit, dubbed "Delayed". The allocation of applications to these groups is shown in Table 1 and Figure 3.

Within the boundaries of the scenario assumptions, the three groups allow for distinct interpretation of challenges and policy suggestions. "**A**dvantaged" applications will largely be decarbonized – under the conditions laid out for this scenario – by 2040 and thus (over-) achieve both EU and the stricter German targets. These applications are advantaged by having access to readily available technologies with comparably low investment, short to medium lifetimes and sometimes relevant efficiency gains of electrification. No additional measures – beyond the strong measures already included in the scenario – seem necessary. Applications within this group are consumers of process heat in the form of steam (in the food, chemical and paper industry) and glass production (flat and container). Similar, "**B**oosted" applications have favourable starting conditions and – with the policy support implemented in the scenario – reach high attractiveness of alternative technologies. They are, however, either attractive later, leaving less time for implementation, or include technologies with higher lifetime. These applications are thus very much able to reach decarbonisation, but require slightly earlier or stronger signals. In this group, casting of iron and other metal processing applications are located. "**C**ornered" applications are a special case. For this group, the solution space's boundary of diffusion limit is of high relevance, as it allows defining this group in the first place. With singular regard to this dimension, these applications are not much different to the "**A**dvantaged" applications – indicating a high potential to adopt technologies. Simply put, these applications can react to changes of attractiveness quickly. They do lack, however, attractive options, some more than other. Within this group, specialized heat treatment applications (hardening, carburization) and heating of semi-finished copper products are located. Given this observation, it can be expected that additional price signals or any other measure increasing the attractiveness of alternative technologies could quickly result in increased market diffusion[12].

"**D**elayed" finally is far from the diffusion limit. Additionally, some members of this group lack – by 2040 –the attractiveness for CO_2-neutral technologies. Main reason why this group does not achieve decarbonisation though is the inability to realize the existing attractiveness in actual market diffusion. This can have two main reasons, similar to "**B**oosted" but more pronounced. These reasons refer to the time available for technology diffusion: First, some applications' alternative technologies "unlock" only by 2030, based on the scenario's assumptions of technology readiness. Efforts to develop these technologies resulting in the plausible assumption they might be available earlier can influence the results. Examples for this are continuous heating and heat treatment of long and flat steel. Second, applications with high technical lifetimes often only allow at most one replacement of an installation in the modelled timeframe. If this replacement happens too early and price signals are not present yet, a fossil installation will be built that cannot be replaced again by 2040. This effect forms a cluster of non-metallic minerals processing (refractory bricks, lime, clinker) with modernisation cycles from 30 up to 60 years. As the dimension time is not represented in Figure 3, it must be noted that another reason is theoretically possible for the behaviour observed in the "**D**elayed" group: If the attractiveness of the alternative technologies quickly increased between e.g. 2038 and 2040 (and was low before), this application would seem to have attractive options but never had the chance to implement them. Within the analysed scenario, there is no such sharp change of conditions, especially not for specific applications. However, the timing of price signals is a dimension worth considering.

We conducted a quick analysis concerning current price levels of natural gas. As a price signal for the model, we used the rough assumption that natural gas prices triple in 2022, partly recovers until 2030 and remain doubled until 2050 – all compared to our base case described above and neglecting any other price changes (e.g. higher electricity prices). In this variation, strong influences on the identified groups can be observed in 2040. Assuming the same ambitious policy package, 56 % (78 TWh) of the investigated energy demand (13 applications) could now be allocated to group "**A**dvantaged". The newly added applications stem from all previous groups. 2 % (2.8 TWh) in 7 applications can be grouped in "**B**oosted". Two applications are present in group "**C**ornered", making up for only less than 1 % (0.1 TWh). Finally, the "**D**elayed" group with 42 % (59 TWh) in 12 applications has a strong momentum to decarbonized technologies, with an average attractiveness of alternative technologies of 84 % – the average over all groups is 90 %. This indicates that the bottleneck is the installation replacement which we didn't increase manually. It seems reasonable to assume, though, that strong price signals would induce a higher replacement rate, further shifting the results.

The technology deployment within the group of alternative (CO_2-neutral) technologies is another dimension worth analysing (Figure 4). Readings example for 2040 (follow the outer ticks): application 4 (continuous heating flat/long steel) has about 86 % share of fossil fuels (horizontal axis, from right to left) and about 13 % of CO_2-neutral fuels (axis from top to bottom right); application 13 (discontinuous homogenizing/heating of aluminum strip/profiles) shows 27 % electric (bottom left to top axis), 10 % CO_2-neutral fuels and 63 % fossil fuels.

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[12] For discontinuous heat treatment of copper (application 18) and continuous carburizing (application 24), high investment seems to be an important barrier. A technology switch, e.g. towards direct electrification, would resemble an investment in a new installation, while the modernisation cycles within the existing fossil technology require much lower effort. The (compared with other applications) high share of CAPEX on total costs of about 40 % thus hampers technology switch.

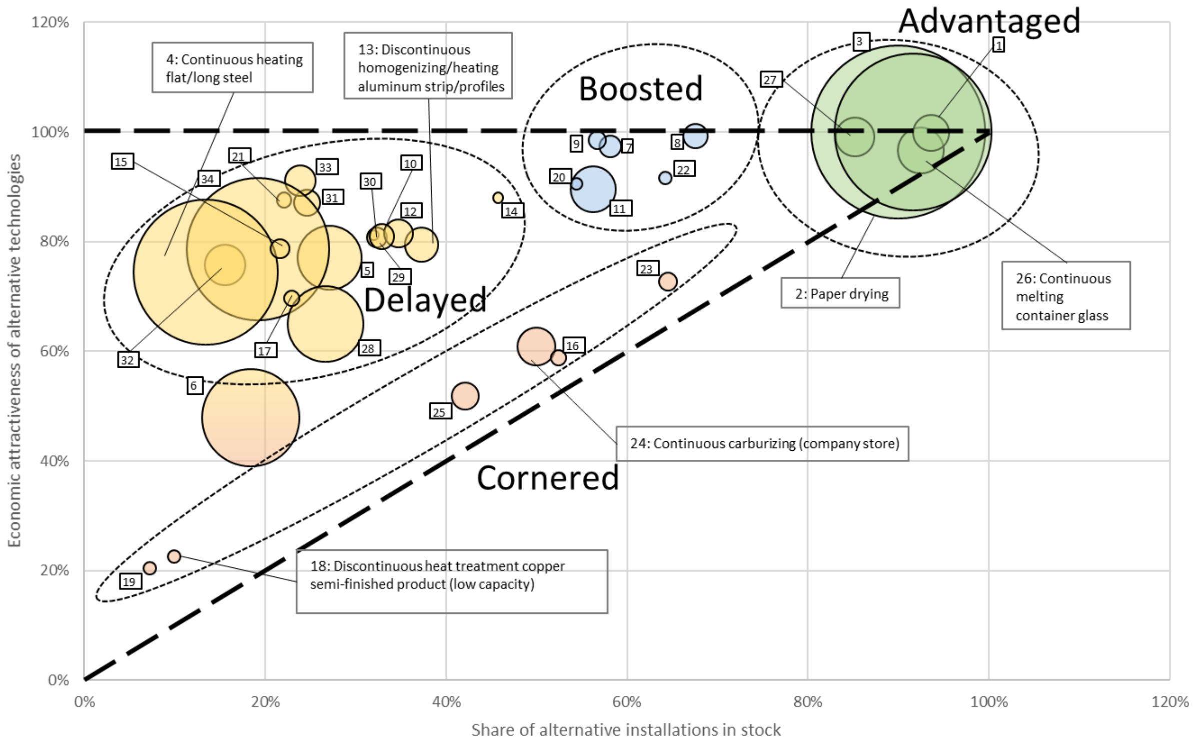

Figure 3. Diffusion results in 2040 with categorization and example applications.

While in 2020 (not displayed), almost all applications rely completely on fossil fuels (lower left corner), they gradually move towards direct electrification (upper corner) or CO_2-neutral fuels (lower right corner). By 2040, the applications reach varying degrees of decarbonisation (also visible in Figure 3) with different technology paths. A stronger trend to direct electrification can be observed, with CO_2-neutral fuels only being used where strong technical reasons exist[13]. This is in part a result of the scenario assumptions, in which the price of electricity-based fuels is a function of the electricity price[14]. Thus, in this scenario, electric heating is, where technically possible, economically more attractive than CO_2-neutral fuels. The relevant observation here is that even with these assumptions, there are niche applications in which CO_2-neutral fuels can be relevant. The applications grouped in "**A**dvantaged" and "**B**oosted" can also be identified here by their higher distance to the fossil fuel use area. However, the groups "**C**ornered" and "**D**elayed" can not be distinguished from each other, both aligning in the lower left, fossil corner. Comparing 2040 and 2050 (top/bottom), there seems to be a trend for the "**D**elayed" to split in two groups, one going for direct electrification, the other one for CO_2-neutral fuels.

Summary and Conclusions

In this contribution, we investigated 34 applications beyond the usually covered basic material production that utilize process heat and need to transform to carbon neutrality by the middle of this century. The applications analysed stand for about 40 % of industrial energy demand in Germany. We applied an ambitious transformation scenario with strong price signals, behaviour change and other supporting policy measures to a techno-economic diffusion model. The main results are economic attractiveness of CO_2-neutral technologies, the diffusion of decarbonized technologies in general and the types of technologies used.

Several limitations of this study need to be mentioned. Foremost, as outlined in Table 1, the investigated applications cover only about 40 % of the industrial energy demand. It is to be expected, that many more applications could be included in such an investigation, for example in the chemical industry and less energy-intensive branches of the economy. The comparably high effort for the definition and analysis required for the approach poses a significantly barrier to its wider use. It should thus be used to complement subsectoral analyses, instead of replacing them. Furthermore, this publication merely presents one of many possible scenarios and policy packages. Albeit the authors have high confidence in the results, their robustness must be substantiated with scenario variations. This includes several assumptions (e.g. price structure of electricity and CO_2-neutral fuels or availability of biomass). Besides lifetime and economic factors on the diffusion of CO_2-neutral technologies, the technical readiness level TRL of technologies has to be considered. In this work, a simplified availability depending on the TRL of a technology is assumed. This may vary and the actual

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[13] Note that the share of CO_2-neutral fuels in Figure 4 is overrepresented, since all hybrid (electrification and CO_2-neutral fuel use in parallel) installations are allocated to this axis.

[14] With the transformation efficiency (assumed to be 70 % for hydrogen, and 50 % for synthetic hydrocarbons) as a factor between them.

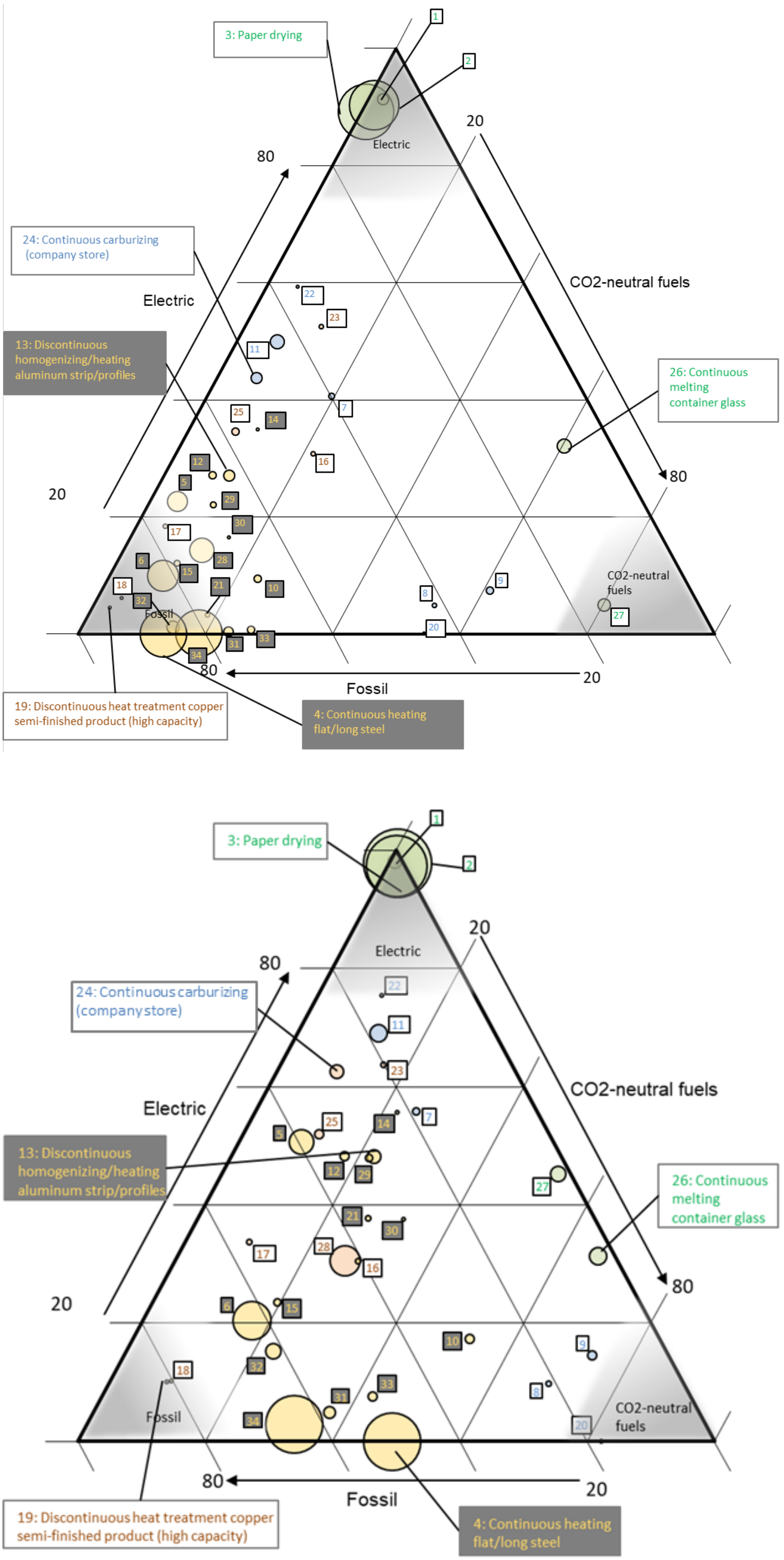

Figure 4. Ternary diagram of technology use by application, top: 2040, bottom: 2050. Size of circles indicates capacity. Hybrid technologies (electricity and CO2-neutral fuels) are allocated to CO_2-neutral fuels. Refer to Table 1 for applications' numbering. Figure created with (Graham and Midgley 2000) toolkit.

availability depends on the research and development activities in a specific field. Finally, while high confidence is attributed to the techno-economic data gathered in the project associated with this publication, even the level of applications is unsuited to describe properties of individual installations and the authors believe that a validation of the conclusions with use cases could be very valuable.

On the dimensions of economic attractiveness and diffusion, we find four distinct groups of applications. According to their behaviour, we call them "**A**dvantaged", "**B**oosted", "**C**ornered" and "**D**elayed" in an effort to summarize their main challenges. "**A**dvantaged" applications are in a good position to decarbonize, with available and competitive technologies. They comprise 52 % (74 TWh) of the investigated energy demand. "**B**oosted" applications see a strong but not sufficient increase in attractiveness and diffusion of CO_2-neutral technologies. They account for about 3 % (5 TWh) of the investigated energy demand in highly specialized applications. "**C**ornered" applications lack economically attractive options to decarbonize, although they would be able to implement them faster than other applications. About 2 % (2 TWh) of the investigated energy demand is in this group. "**D**elayed" applications, with 43 % (60 TWh) of investigated energy demand and 17 of the 34 applications, have by 2040, economically attractive options. For several reasons – that vary among its members – this attractiveness is not leading to fast enough diffusion, though.

We conclude that the challenges to successful decarbonisation can not be described sufficiently on a subsectoral basis, but their heterogeneity extends at least to the application-level investigated here. The availability and economic attractiveness of CO_2-neutral technologies can vary within seemingly similar activities. Policy design should thus strive to address these challenges specifically along the two dimensions of technology attractiveness and technology diffusion, as presented as groups in this publication. In short, these challenges are: For group "**A**dvantaged", the assumed – ambitious – measures suffice to allow high diffusion of CO_2-neutral technologies by 2040. But they are still more ambitious than any planned or enacted policy. For group "**B**oosted", even stronger economic incentives and behavioural change seems necessary. For group "**C**ornered", CO_2-neutral technologies must be available earlier than currently expected, hinting at increased effort for research, development and distribution. For group "Delayed", both early price signals and much faster installation replacement are needed. For all groups, regulatory law should be considered to facilitate fast replacement of old installations and stop installation of new fossil ones.

Publication bibliography

Aden, Nate (2018): Necessary but not sufficient: the role of energy efficiency in industrial sector low-carbon transformation. In *Energy Efficiency* 11 (5), pp. 1083–1101. DOI: 10.1007/s12053-017-9570-z.

AGEB e. V. (2020): Bilanzen 1990 bis 2019. Available online at https://ag-energiebilanzen.de/daten-und-fakten/bilanzen-1990-bis-2019/?wpv-jahresbereich-bilanz=2011-2020, checked on 2/22/2022.

Allwood, Julian M.; Cullen, Jonathan M.; Milford, Rachel L. (2010): Options for achieving a 50 % cut in industrial carbon emissions by 2050. In *Environmental science & technology* 44 (6), pp. 1888–1894. DOI: 10.1021/es902909k.

An, Runying; Yu, Biying; Li, Ru; Wei, Yi-Ming (2018): Potential of energy savings and CO_2 emission reduction in China's iron and steel industry. In *Applied Energy* 226, pp. 862–880. DOI: 10.1016/j.apenergy.2018.06.044.

Arens, Marlene; Worrell, Ernst; Eichhammer, Wolfgang; Hasanbeigi, Ali; Zhang, Qi (2017): Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany. In *Journal of Cleaner Production* 163, pp. 84–98. DOI: 10.1016/j.jclepro.2015.12.097.

Bataille, Chris; Åhman, Max; Neuhoff, Karsten; Nilsson, Lars J.; Fischedick, Manfred; Lechtenböhmer, Stefan et al. (2018): A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. In *Journal of Cleaner Production* 187, pp. 960–973. DOI: 10.1016/j.jclepro.2018.03.107.

Bataille, Chris; Jaccard, Mark; Nyboer, John; Rivers, Nic (2006): Towards General Equilibrium in a Technology-Rich Model with Empirically Estimated Behavioural Parameters. Available online at https://www.semanticscholar.org/paper/Towards-General-Equilibrium-in-a-Technology-Rich-Bataille-Jaccard/93b9334c669112c0f04c2b379c169d640f9395fb, checked on 1/17/2022.

BDEW (2021): Strompreisanalyse 2021. Available online at https://www.bdew.de/service/daten-und-grafiken/bdew-strompreisanalyse/, checked on 1/17/2022.

Cuviella-Suárez, Carlos; Colmenar-Santos, Antonio; Borge-Diez, David (2021): Correction to: Thermal energy reduction in sanitary-ware industry by heat-recovering thermal engineering technologies. In *Energy Efficiency* 14 (8). DOI: 10.1007/s12053-021-10012-x.

Dolianitis, Ioannis; Giannakopoulos, Dionysios; Hatzilau, Christina-Stavrula; Karellas, Sotirios; Kakaras, Emmanuil; Nikolova, Evelina et al. (2016): Waste heat recovery at the glass industry with the intervention of batch and cullet preheating. In *Therm sci* 20 (4), pp. 1245–1258. DOI: 10.2298/TSCI151127079D.

EUROSTAT (2021a): Electricity prices for non-household consumers (nrg_pc_205). Available online at https://ec.europa.eu/eurostat/data/database, checked on 1/17/2022.

EUROSTAT (2021b): Gas prices for non-household consumers (nrg_pc_203). Available online at https://ec.europa.eu/eurostat/data/database, checked on 1/17/2022.

Fais, Birgit; Sabio, Nagore; Strachan, Neil (2016): The critical role of the industrial sector in reaching long-term emission reduction, energy efficiency and renewable targets. In *Applied Energy* 162, pp. 699–712. DOI: 10.1016/j.apenergy.2015.10.112.

Fleiter, Tobias; Fehrenbach, Daniel; Worrell, Ernst; Eichhammer, Wolfgang (2012): Energy efficiency in the German pulp and paper industry – A model-based assessment of saving potentials. In *Energy* 40 (1), pp. 84–99. DOI: 10.1016/j.energy.2012.02.025.

Frassine, C.; Rohde, C.; Hirzel, S. (2016): Energy saving options for industrial furnaces – the example of the glass industry. ECEEE Industrial Summer Study Proceedings.

Fraunhofer ISI (2021a): Internet portal for the Langfristszenarien 3 (long-term scenarios). Available online at https://

www.langfristszenarien.de/enertile-explorer-de/, checked on 1/17/2022.

Fraunhofer ISI (2021b): Model homepage FORECAST. Available online at https://www.forecast-model.eu/forecast-en/index.php, checked on 1/17/2022.

Graham, David J.; Midgley, nicholas G. (2000): GRAPHICAL REPRESENTATION OF PARTICLE SHAPE USING TRIANGULAR DIAGRAMS: AN EXCEL SPREADSHEET METHOD. In *Earth Surface Processes and Landforms* 2000 (25), pp. 1473–1477. Available online at https://www.lboro.ac.uk/microsites/research/phys-geog/tri-plot/index.html, checked on 2/23/2022.

IOB RWTH (Ed.) (2021): 3. Aachener Ofenbau- und Thermoprozess-Kolloquium. AOTK 2021. Aachen, 7.-8.10. 2021.

Lechtenböhmer, Stefan; Nilsson, Lars J.; Åhman, Max; Schneider, Clemens (2016): Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand. In *Energy* 115, pp. 1623–1631. DOI: 10.1016/j.energy.2016.07.110.

Napp, T. A.; Gambhir, A.; Hills, T. P.; Florin, N.; Fennell, P.S (2014): A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries. In *Renewable and Sustainable Energy Reviews* 30, pp. 616–640. DOI: 10.1016/j.rser.2013.10.036.

Neuwirth, Marius; Fleiter, Tobias; Manz, Pia; Hofmann, René (2022): The future potential hydrogen demand in energy-intensive industries – a site-specific approach applied to Germany. In *Energy Conversion and Management* 252, p. 115052. DOI: 10.1016/j.enconman.2021.115052.

Rehfeldt, M.; Neusel, L.; Neuwirth, M. (2021a): CO_2-neutrale Prozesswärmeerzeugung in heterogenen Anwendungen – Ein Diffusionsmodell mit hoher Auflösung. Available online at https://iewt2021.eeg.tuwien.ac.at/download/contribution/fullpaper/85/85_fullpaper_20210831_074847.pdf

Rehfeldt, Matthias; Fleiter, Tobias; Worrell, Ernst (2018): Inter-fuel substitution in European industry: A random utility approach on industrial heat demand. In *Journal of Cleaner Production* 187, pp. 98–110. DOI: 10.1016/j.jclepro.2018.03.179.

Rehfeldt, Matthias; Schwotzer, C.; Kaiser, F.; Neusel, L. (2021b): Dekarbonisierung von Prozesswärme: Kosten, Handlungsoptionen und Politikempfehlungen, pp. 23–38.

Rissman, J.; Bataille, C.; Masanet, E.; Aden, N.; Morrow, W. R.; Zhou, N. et al. (2020): Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. In *Applied Energy* 266, p. 114848. DOI: 10.1016/j.apenergy.2020.114848.

Schmitz, N.; Sankowski, L.; Kaiser, F.; Schwotzer, C.; Echterhof, T.; Pfeifer, H. (2021): Towards CO_2-neutral process heat generation for continuous reheating furnaces in steel hot rolling mills – A case study. In *Energy* 224, p. 120155. DOI: 10.1016/j.energy.2021.120155.

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[15] CO_2-neutrale Prozesswärmeerzeugung - Umbau des industriellen Anlagenparks im Rahmen der Energiewende: Ermittlung des aktuellen SdT und des weiteren Handlungsbedarfs zum Einsatz strombasierter Prozesswärmeanlagen, UBA FKZ 3718410030, duration: April 2019 – February 2022