

Still alive, but different in the future?

Decarbonisation of industrial steam boilers from a multi-dimensional perspective

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Abstract

The first steam applications were already invented two millennia ago; due to its versatility, industry will still need steam in the future. In view of the current climate targets, a shift towards carbon-free steam-generation is required while it is still mostly based on fossil fuels today. Future alternatives that are based on the direct use of renewable electricity or green hydrogen are not yet economically favourable or they are still under development, also due to the comparatively high electricity prices. This paper therefore investigates CO₂-neutral steam generation in two respects: First, compared to the current state of the art, which electricity-based technologies are available for steam generation and what is their development status? And second, how are the technologies evaluated in comparison to the current fossil reference technology from a multi-dimensional perspective encompassing ecological, economic and technical criteria? In this paper, these questions are addressed along three applications for steam generation in the paper, food and chemical industries. For this purpose, a concept for a multi-dimensional analysis with a perspective up to the year 2050 is introduced and applied. The required data was obtained from literature, a quantitative model and 19 semi-structured interviews with industry representatives, manufacturers and research institutions. The results indicate that various alternative technologies (electrode boilers, heat pumps, hydrogen-fired

steam boilers) are available, but their technology readiness level varies. To contribute to their widespread deployment in industry, policy making will have to ensure competitive economic as well as ecological and infrastructural framework conditions with a long-term perspective.

Introduction

To mitigate the consequences of global warming, policy makers in many countries strive to substantially reduce greenhouse gas (GHG) emissions in the decades to come. The European Union seeks to achieve climate neutrality by 2050, while under the Federal Climate Protection Act amended in 2021, the German government aims at it by 2045. The industry sector in Germany accounted for around 24 % of GHG emissions in 2020 and thus has an important role for decarbonisation (Umweltbundesamt 2021). Important activities in this sector focus on emission-intensive processes from producing crude steel, cement and lime and selected basic chemicals. Yet these only account for about 50 % of the process heat demand with the rest of the demand attributed to other, often very heterogeneous plants, industrial furnaces and steam generators (Rehfeldt et al. 2021). About three quarters of the final energy consumption for heat generation in the range between 100 and 500 °C are accounted for by the paper, food and chemical industries alone (in 2013, Kemmler et al. 2017). The provision of thermal energy in the form of process steam plays an important role in these as well as other sectors (e.g. Fleiter, T. Steinbach, J. and Ragwitz 2016).

Nowadays, industrial steam generation is almost exclusively based on fossil fuels. Future alternatives for CO₂-neutral steam generation include the direct use of renewable electricity (elec-

trode boilers, heat pumps) and hydrogen produced by electrolysis (hydrogen-fired steam boilers). Compared to decarbonizing processes of heavy industries, their charm lies in the large number of plants and the sectoral independence (Einstein et al. 2001): Thus, there is a large market where alternative steam generation solutions can be deployed largely “off-the-shelf”. Yet such alternatives are not yet economically favourable or they are still under technical development, also because of unfavourably high electricity prices. Corresponding studies show that appropriate incentives and falling energy costs for electricity and hydrogen could promote the diffusion of such technologies (Rehfeldt et al. 2021; Wei et al. 2019).

While novel steam generator technologies may yield substantial advantages in reducing GHG emissions, there are various ecological, economic and technological aspects that can be taken into consideration to have a clear understanding of their impact to rule out potentially detrimental aspects in case of a broader diffusion of these technologies. Furthermore, with a perspective towards 2050, technological progress and changing framework conditions need to be considered.

Against this background, this paper aims to investigate on alternate options for decarbonizing steam-generation and to review them from a multi-dimensional perspective by addressing the following **research questions**:

- First, compared to the current state-of-the art, which electricity-based technologies are available for steam generation and what is their current development status?
- And second, how are these technologies alternatives evaluated compared to the current fossil reference technologies from a multi-dimensional perspective?

To answer these questions, three applications of steam generation in the paper, food and chemical industries are investigated as examples for a holistic assessment of CO₂-neutral steam generation using a multi-dimensional analysis (MDA). The development is investigated in ten year steps until 2050. In the following, the paper describes the chosen methodology, it then presents and discusses the obtained findings of the MDA and finally provides a set of conclusions.

Methodology

The methodology for the investigation on future steam generation technologies encompasses the following steps:

1. Identification and characterization of alternative steam generation technologies
2. Technological analysis of steam generators in the applications
3. Development of an MDA for the steam generation techniques
4. Data acquisition for the MDA and result analysis

For the three industrial “sectors” under investigation (e.g. food industry), specific “applications” (e.g. milk powder production) are defined. For each application, several “techniques” are available to provide steam. These “techniques” are derived from cross-sectoral “technologies” such as direct electrification or hydrogen combustion. In the context of the MDA, fossil

“reference techniques” (e.g. fossil-fired steam boiler) and CO₂-neutral “alternative techniques” (e.g. electric heat pump) are compared. The steam-generating unit itself serves as the system boundary: The downstream production processes are only defined on the basis of the required steam demand.

STEP #1: IDENTIFICATION OF ALTERNATIVE STEAM GENERATION TECHNOLOGIES

State-of-the art and future steam-generating technologies and their development status and techno-economic characteristics (efficiency, investment, service life, etc.) are identified on a cross-sectoral aggregated level. The selection of the main technologies considered was derived from literature and validated in subsequent interviews. Within the framework of the MDA outlined below, these technologies are assessed against a set of qualitative criteria.

STEP #2: TECHNOLOGICAL ANALYSIS OF STEAM GENERATORS IN THE APPLICATIONS

To investigate the influence of process- and sector-specific characteristics (e. g. operation mode, steam demand, steam pressure and temperature, energy carrier, etc.) with regard to quantitative criteria such as GHG emissions and investment, three representative steam applications are selected from the industries under consideration (paper, food and chemical industry). Certain criteria are applied for the selection: For industries with a heterogeneous product range, such as the food and chemical industries, an exemplary application is selected that sufficiently describes the characteristics of steam utilisation. In addition to selecting thermal processes that are as representative as possible, coverage of various relevant temperature levels is achieved at the same time. This also applies to the use of possible alternative techniques for steam generation within an application. For example, milk powder drying requires temperatures of up to 240 °C, which cannot be provided by commercially available heat pumps today. Drying temperatures of up to 120 °C, as required in the paper industry, for instance, can already be technically realised today with high-temperature heat pumps. For the evaluation of the alternative technique “heat pump” with regard to its application potential, a differentiated consideration of temperature levels is therefore necessary and possible by the chosen applications. Hence, the later used reference and alternative techniques for steam generation are technologies that are further differentiated for each of the three applications. For example, the technological readiness level (TRL) and the coefficient of performance (COP) of the heat pump differ depending on the steam temperature it has to provide. Within the framework of the MDA approach outlined below, the application-specific reference and alternative techniques are assessed against a set of quantitative criteria.

STEP #3: MULTI-DIMENSIONAL ANALYSIS (MDA)

The aim of the MDA is to provide orientation and to contribute to a holistic understanding of different types of steam generators, also with regard to future developments. Key requirements to the methodology include a simple, pragmatic, broadly applicable and transparent approach. Numerous methods and applications for multi-criteria assessments have been suggested, differing considerably in term of underlying axioms, data requirements and involvement of decision-makers. For specifi-

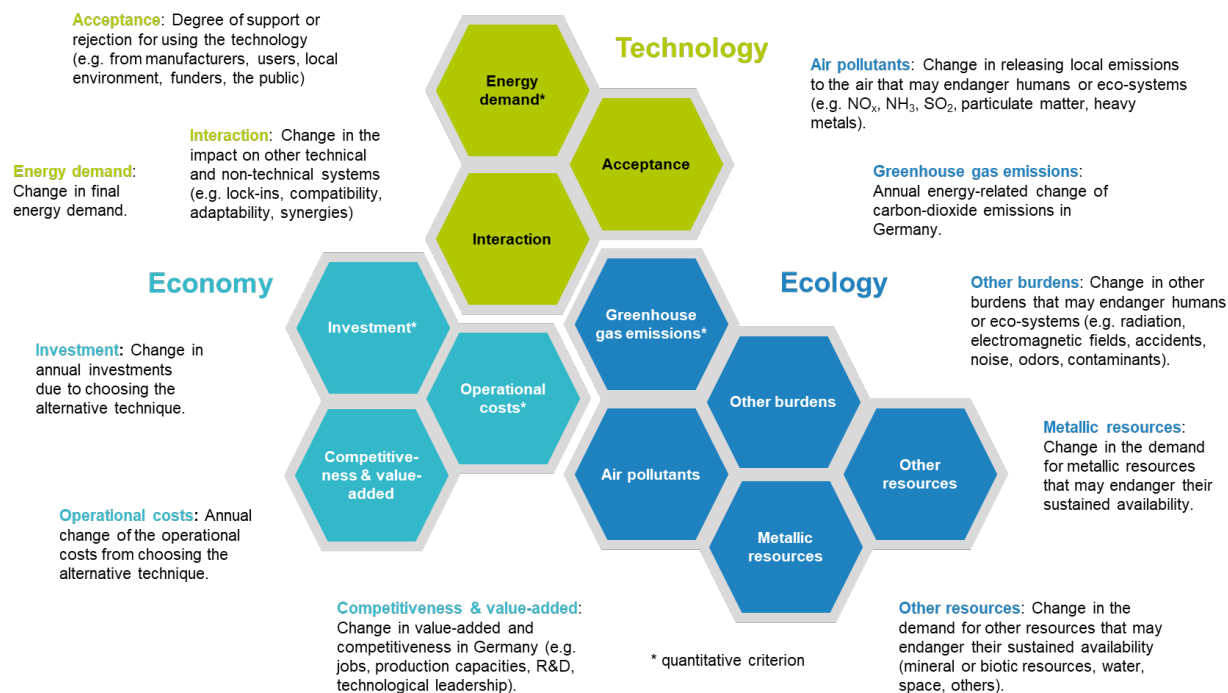


Figure 1. Overview of the 11 MDA-criteria including their description.

cally assessing the techniques in this analysis, straight-forward methods for analysing funding opportunities in energy technologies used in Germany were adopted here (Viebahn et al. 2017; Wietschel et al. 2010).

The basic idea of the method is to do pairwise comparison of alternatives as in many multi-criteria methods. For this purpose, the MDA uses state-of-the art reference techniques mostly based on fossil fuels to compare them to innovative alternatives. These comparisons are carried out along 11 largely independent criteria in three groups that cover aspects related to operation of steam generators (Figure 1). To ensure the ease of application, seven criteria are chosen as qualitative criteria with a 5-point-scale (from “no change” to “substantially more positive/negative”) and the remaining four are quantitative criteria. For each criterion, information for the years 2020, 2030, 2040 and 2050 is required. To ensure a harmonized understanding and application of the criteria, a common implementation guideline is available. It includes, among others, a definition and interpretation of each criterion, also concerning the interpretation of the scales and values, various support questions/items to ensure a harmonized use and requirements to documentation. To facilitate practical utilization in the analysis carried out here, an Excel-based template was developed alongside for processing each application.

STEP #4: DATA ACQUISITION FOR THE MDA AND RESULT ANALYSIS

The data acquisition is based on a mix of methods including starting with a literature review, subsequent expert interviews and the use of a techno-economic diffusion model for quantitative criteria.

The process covered information from 19 semi-structured interviews with German industry representatives from paper, food and chemical industries (6) and associations (4), as well as manufacturers (4) and research institutions (5) mainly from

Germany but also from Austria, Denmark and Norway. In addition to technical data, the interviews covered economic aspects, as well as the topic of decarbonisation. To fully understand the specific characteristics of each application, a catalogue of criteria and questions was drawn up for the interviews. This included around 60 parameters (e.g. steam demand and temperature, production volume, number of plants, etc.) as well as questions on the MDA-criteria from figure 1 (e.g. compatibility with current/future energy supply structures as part of the criteria “interaction”). For each alternative technique (electrode boiler, heat pump, hydrogen boiler), the manufacturers also filled out a corresponding catalogue of criteria. In addition, accompanying research was carried out, including databases of relevant public institutions (Eurostat, Federal Statistical Office).

For the quantitative criteria, partial results from the upstream techno-economic diffusion model are used, which in particular contain information on emissions, specific energy consumption, representative capacities and economic parameters for each steam-application and its techniques. The model itself enables the calculation of the economic viability, attractiveness and diffusion of CO₂-neutral process heat generation. On the basis of economic and technical properties, it maps the competition between fossil reference and CO₂-neutral alternative technologies for specific applications. Exemplary policy measures can be applied – from price signals to behavioural change to regulatory law – that could enable completely CO₂-neutral process heat generation in 2050 (for a detailed description, see Rehfeldt et al. 2021).

Concerning the results, it has to be noted that the quantitative techno-economic results cover a large number of parameters for the underlying diffusion model. As described by Rehfeldt et al. (2021), a “package of measures” has been selected here which leads to a largely decarbonised steam supply in 2050 for the applications considered (“stage 3”). Important meas-

ures are an ambitious CO₂ price path (from today's €55/t CO₂ to €300/tCO₂ by 2050) and further price signals to reduce the electricity price (electricity rate relief, etc.). For further details including the energy carrier and CO₂ prices and emission factors, please refer to Rehfeldt et al. (2021). Under the specified conditions, far-reaching decarbonisation is achieved in the applications considered here.

Results

INDUSTRIAL STEAM GENERATION: REFERENCE AND ALTERNATIVE TECHNOLOGIES

Boilers are commonly used as steam generation systems and are a part of almost every major industrial process today (Beck et al. 2021). They are still primarily powered by fossil fuels (Einstein et al. 2001). Boilers in use are water tube and shell boilers types (Aydemir et al. 2015; Rohde et al. 2014, also see Table 2). In the paper, food and chemical industries, these are used in common natural gas-fired boilers or CHP-plants.

The development of cost-efficient alternatives to fossil steam generation is considered necessary for a rapid transition towards renewables-based steam production (Beck et al. 2021). In this context, electrical conversion technologies such as power-to-heat or power-to-gas are considered important (e.g. Rissman et al. 2020; Wei et al. 2019) and are therefore also the focus of this study. Based on a bottom-up approach, electrification in low-temperature energy services such as steam, in tandem with a rapidly decarbonising and expanding power grid, is seen as one part of four overarching pillars (energy efficiency, material efficiency, industry-specific, and power grid) that lead to both energy and CO₂ savings in a relatively short term (Worrell and Boyd 2022).

Electrode boilers as an electricity-based steam boiler technology are commercially established as a standard product for large-scale use (system proof to market) (PARAT Halvorsen AS 2021; Agora Energiewende 2019). According to the expert interviews, electrode boilers are used today as a niche product to supplement conventional steam generation due to their high flexibility potential. Manufacturers state, that in general, many systems or components can be reused when converting from a natural gas to an electrode boiler. This depends on the age of the gas boiler system and must be checked in each individual case. Another promising technology for steam generation are **high-temperature heat pumps (HTHP)**. Usually driven by electricity, they can be relatively easily integrated into low-temperature steam networks, which are widely used in industry (Zühlsdorf et al. 2019; Wilk et al. 2019; Wolf et al. 2012). A study of Arpagaus et al. shows a selection of 26 HTHP from 15 manufacturers for industrial and commercial use that can provide steam of up to 160 °C currently, but only cover the small power range (<1 MW) (Arpagaus et al. 2018)¹. Industrial

steam applications usually require larger quantities of steam. According to estimates by manufacturers and researchers, the scalability of current HTHP systems towards larger steam outputs is technically possible, similar to large heat pumps in district heating or compressors in power plant turbines. However, according to the interviews, heat pumps for steam generation seem to be used only to a very limited extent outside pilot plants so far. In particular, the further development of refrigerants with high critical temperatures and low global warming potential (GWP) and of new compressors lead to the expectation of a further increase in the achievable temperatures and output sizes in the short to medium term (as also stated in Wolf 2016). Arpagaus et al. describes for example, 18 experimental research projects at international level on HTHP with sink temperatures above 100 °C (Arpagaus et al. 2018; Wemmers et al. 2017; Wilk et al. 2017; Wilk et al. 2020; Zühlsdorf et al. 2019; IEA Heat Pump Centre 2014b, 2014a). Another option are industrial steam boilers for the use of up to 100 % hydrogen (Gosse 2019). According to the interviews, **hydrogen-fired steam boilers** are commercially available for large-scale use and are already used in some instances in industries with internal hydrogen flows, such as the chemical industry². By means of a comparatively simple conversion of existing natural gas boilers, according to manufacturers, a future changeover to hydrogen only requires a renewal of the burner including gas supply and an increased effort in exhaust gas after-treatment. However, due to the changed combustion properties, there seems to be a need for further research in the field of burner technology, especially for the use of hybrid solutions in combination with natural gas. Various companies are developing new types of hydrogen burners for industrial use (E&M Combustión S. L. 2019; Toyota Motor Corporation 2021; Elavarasan et al. 2018; Schönfelder 2020).

A wrap-up of the state of development of the previously discussed technologies is available in Table 1. The research and development (R&D) requirement is assessed by means of the TRL. For example, the TRL and COP of heat pumps differ depending on the steam temperature they have to provide (also see Table 2).

For the subsequent analysis, the natural gas-fired steam boiler and/or the CHP plant are used as **reference technique** due to their currently widespread application, and electrode boilers, HTHP and hydrogen-fired steam boilers are used as future **alternatives** based on direct electrification or hydrogen combustion.

TECHNO-ECONOMIC CHARACTERISTICS

Typical techno-economic characteristics presented in Table 2, show that the alternative technologies studied differ in terms of steam output, maximum achievable temperature and pressure, and in terms of typical investments. These characteristics were validated within the interviews before they were further specified within the three applications (see next section). More details on the resulting techno-economic data sets for each of the three applications, required for the upstream diffusion model

1. While slightly more than half of the 26 HTHP use alternative refrigerants (HFO or natural refrigerants) with low global warming potential (GWP), almost half are still operated with HFC refrigerants, which will, however, be restricted in the foreseeable future under the F-Gas regulation due to their high GWP of more than 150. The industrial benchmark is represented by the Japanese heat pump model Kobleco SGH 120/165 with a sink temperature of up to 165 °C and a heating capacity of about 370 kW. In Japan, this system has already been successfully integrated in 7 plants in the chemical industry (Kaida et al.).

2. also see https://www.bosch-thermotechnology.com/de/media/country_pool/knowledge/technical_reports/fachbericht-wasserstoff.pdf (checked on 02/02/2022)

Table 1. Development status of the alternative techniques under consideration.

	Electrode boiler	High-temperature heat pump system	Hydrogen-fired steam boiler system
Technology readiness level	TRL 9: Actual system proven in operational environment	TRL 7-8 for HTHP up to 160°C: System prototype demonstration in operational environment ¹ TRL 5-6 for HTHP up to 240°C: Technology validated in relevant environment ²	TRL 9: Actual system proven in operational environment
State of development/ Market-readiness	Industrial electrode boilers are commercially available as standard product for large-scale use, but tend to be used as a niche product to exploit flexibility potential.	There is a tendency for HTHP prototypes above 100 °C to be under development, with a steadily growing range of products on the market. Some HTHP up to 165 °C are already commercially available, but with comparatively low steam capacities (about 1-2 t/h).	Hydrogen-fired industrial boilers are commercially available for large-scale use. So-called H ₂ -ready boilers allow a simplified conversion to hydrogen at a later stage.
Expected commercialisation	Already available	HTHP up to 160°C/240°C earliest 2025/2030 for large-scale use	Already available
Further R&D until 2050	Research is currently being conducted into materials for use at high pressures (> 300 °C/90 bar). However, the development goals focus more on the dynamic application and the necessary economic and legal framework conditions necessary. Efforts by manufacturers to reduce plant costs focus on increasing sales volumes.	Future research activities focus on increasing efficiency and developing new synthetic refrigerants with high critical temperatures and low GWP as well as the use of natural refrigerants. Research is also being conducted on the optimisation of heat pump systems and improved system integration (including heat exchangers, compressors and new control systems) for improved flexibility.	Pure hydrogen combustion from residual products of processes is already technically feasible. Technical challenges arise with premixing systems to provide standardised mixtures due to the high flame speeds and possible flashbacks. Hybrid systems in combination with natural gas therefore require additional control mechanisms. Various companies are developing novel hydrogen burners for industrial use.

1 The classification in TRL<9 is mainly due to the fact that no corresponding systems have yet been realised for economic reasons. Currently available individual HTHP achieve comparatively low steam capacities, which requires corresponding scaling. Based on the data collected, it seems likely that market maturity can be achieved more quickly than implied by TRL 7.

2 For the applications of milk powder production and chemical park steam supply, HTHP systems with steam temperatures of up to 240 °C are needed. Such a system is not yet available or tested, but according to Bühler et al. it is technically feasible and corresponding compressors are already in use in power plant turbines (Bühler et al. 2019).

as well as the quantitative MDA-part, can be found in Rehfeldt et al. (2021).

APPLICATIONS IN THE TARGETED INDUSTRIAL SECTORS

The three exemplary applications are described in the following. An overview of their respective reference and alternative techniques are given in Table 4.

Application 1: Paper drying

Thermal drying is highly energy- or steam-intensive and important in the paper, food and chemical industries (Larsen 2011). Typical drying temperatures are usually between 100 and 200 °C (Wilk et al. 2016). Paper drying is a representative steam application for drying processes with comparatively moderate temperatures around 140 to 150 °C (~4 bar saturated steam) (Suhr et al. 2015; Ghosh 2011). The setup of this application's steam demand (~ 40 MW and 60 t_{steam}/h) is based on

investigations in four paper mills and data on the dryer section from a Sankey diagram of a paper machine (Treppe et al. 2012; Suhr et al. 2015).

Concerning the considered steam generation techniques, a natural gas boiler is used as reference as a common energy source in paper production plants. As pulp and paper mills often also operate heat-controlled CHP plants, these are included as an alternative technique, even if they are fossil-based. In terms of low-CO₂ alternatives, electrode and hydrogen boilers as market-ready alternatives (TRL 9) are used as well as a HTHP system with a COP of 1.9 at 30 °C source temperature using available waste heat (TRL 7-8)³. Similar COPs for the use

3. The measured exhaust air temperature at the exhaust air tower of an exemplary paper machine results in an average temperature level of about 50 °C (Treppe et al. 2012). Cooling the warm, moist exhaust air to 30 °C would mean that more energy can be recovered from the exhaust gas flow (Wilk et al. 2017).

Table 2. Techno-economic characteristics of the reference and alternative techniques under consideration.

	Natural gas-fired steam boiler (shell/ water tube)	Electrode boiler	High-temperature heat pump system	Hydrogen-fired steam boiler	Ref.
Steam temperature	100 up to 300 °C/ 600 °C	100 up to 350 °C (with additional superheater up to 500 °C)	90 up to 165 °C depending on refrigerant	Identical to gas boiler ³	[1], [3], [4], [5]
Steam pressure	max. 30 bar/ max. 300 bar ¹	max. 85 bar	max. 80 bar depending on compressor	Identical to gas boiler ³	[1], [3], [4], [5]
Steam capacity	max. 30 t/h/ max. 200-300 t/h	max. 90 t/h	up to 1 t/h ²	Identical to gas boiler ³	[1], [3], [4], [5]
Efficiency	92 % (stock) 94-97 % (modern systems with economiser)	99 %	COP from 1,6 to 5,8 at a temperature range from 130 to 25K	95 %	[1], [2], [4]
Power range	100 kW up to 50 MW	100 kW up to 60 MW	30 kW up to 20 MW	Identical to gas boiler ³	[2], [3], [4]
Investment	60 €/kW	80 €/kW	~ 400-800 €/kW	80 €/kW	[2], [4]

1 Supercritical up to 350 bar and 2000 t/h.

2 Data of the model Kobelco SGH 165 (single unit).

3 Refers to shell boilers (according to manufacturer, Dodds et al. 2015).

References: [1] Gentili et al. 2014 [2] Danish Energy Agency and Energinet 2020 [3] PARAT Halvorsen AS 2021 [4] Arpagaus et al. 2018 [5] Gosse 2019; additional expert interviews.

of heat pumps in the paper industry were assumed in various studies (Wilk et al. 2017; Treppe et al. 2012).

Application 2: Milk powder production

Milk powder production is chosen as a representative steam application among the processes in the food industry that yields quite heterogeneous products. As compared to the paper drying process, it is a particularly ambitious industrial drying processes with a drying temperature of up to 240 °C (~25 bar saturated steam, Bühler et al. 2019). Due to the high temperature level, currently available HTHP reach their technical limits here. The setup for this application's steam demand⁴ (~20 MW and 30 t_{steam}/h) is based on a publication dealing with the electrification of an energetically optimised milk powder factory in a real Danish production site with five spray dryers (Bühler et al. 2019).

Concerning the considered steam generation techniques, natural gas-fired CHP plants are chosen as reference technique because, according to industry experts, they are predominantly used in milk powder production due to the comparatively large production facilities. In terms of low CO₂-alternatives, in addition to electrode and hydrogen boilers, two different cascade HTHP systems are defined on the basis of Bühler et al. (2019). The first is a central heat pump system and a combination of six commercially available compression heat pumps that provide hot water with a sink temperature of up to 85 °C and a three-stage heat pump system that provides the 210 °C hot steam

for the drying process. Such a three-stage system with turbo-compressor is currently not yet available, but corresponding compressors are already in use in power plant turbines (total system~TRL 5-6) (Bühler et al. 2019). The second, a decentralised heat pump system, in which only commercially available techniques are used in comparison, provides heat (and cold) directly to the respective processes, requiring only a minimum of additional infrastructure. It combines seven commercially available heat pumps that use surplus heat from the process and raise it to 85 °C or 140 °C and an additional electrode boiler for the temperature lift from 140 °C to 210 °C (TRL 7-8) (Bühler et al. 2019).

Application 3: Chemical park steam supply

The two previous applications span a range that allows the approximation of broad (drying) applications in industry. In the chemical industry that yields quite heterogeneous products, steam-generation is largely process-independent. Therefore, a central steam supply of a typical medium-sized chemical park with several pressure levels has been selected as the application. This mainly covers energy-intensive companies producing basic chemicals, but also speciality chemicals to some extent. The setup for this application's steam demand (~400 MW and 550 t_{steam}/h) is based on a separate investigation on the energy demand and energy plants of large German chemical parks.

In terms of reference, natural gas is chosen for a heat-controlled CHP plant combined with peak-load steam boilers. In addition to electrode and hydrogen boilers, two different HTHP systems are defined as low CO₂-alternatives: A HTHP system with COP 2.4, based on currently commercially available heat pumps, which takes over steam generation in the low-

4. The entire milk powder production is considered as application, with drying as the most energy-intensive step representing the central process.

Table 3. MDA results of qualitative criteria (green: positive change, red: negative change).

Criterion	Reference				Electrode boiler				High-temperature heat pump system				Hydrogen-fired steam boiler			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
	Natural gas-fired steam boiler or CHP-plant															
Air pollutants	Ref.	Ref.	Ref.	Ref.	++	++	++	++	++	++	++	++	-	o	o	o
Other burdens	Ref.	Ref.	Ref.	Ref.	o	o	o	o	o	o	o	o	o	o	o	o
Metallic resources	Ref.	Ref.	Ref.	Ref.	o	o	o	o	o	o	o	o	o	o	o	o
Other resources	Ref.	Ref.	Ref.	Ref.	+	+	+	+	+	+	+	+	o	o	o	o
Interaction	Ref.	Ref.	Ref.	Ref.	-	-	o	+	-	o	+	+	--	-	o	+
Acceptance	Ref.	Ref.	Ref.	Ref.	o	+	++	++	+	++	++	+	o	+	++	++
Competitiveness and value-added	Ref.	Ref.	Ref.	Ref.	o	+	+	++	+	+	++	+	o	+	+	++

pressure range (LP) (6 bar/160 °C sink temperature). Furthermore, an ambitious HTHP system with COP 1.6, which takes over steam generation in the low- and medium-pressure range (LP/MP) (25 bar/220 °C sink temperature)⁵. The remaining steam required is provided in each case by an additional electrode boiler.

MULTI-DIMENSIONAL ANALYSIS (MDA) RESULTS

Using the defined techniques and applications, the MDA was carried out by compiling information from literature, expert interviews and quantitative modelling based on this information. It was found that the qualitative criteria under consideration depend mainly on the chosen technologies and not substantially on the applications. These qualitative results are shown first, before proceeding to the quantitative and application-dependent quantitative criteria.

Qualitative criteria

Table 3 shows the results of the qualitative criteria from 2020 to 2050 for each comparison of the alternatives with the reference. Green cells in this table indicate a positive change (+: slight improvement; ++: substantial improvement; negative: vice-versa), red cells a negative change and grey cells no identified change. HTHP are assumed to be available no earlier than between 2025 to 2030.

From this table and its underlying information, the following key results can be summarised along the criteria from Figure 1:

- **Air pollutants:** A positive trend is generally assumed with regard to the release of air pollutants. Changes are in particular expected in the area of NO_x-emissions. In the case of a switch to electricity-based alternative technologies (electrode boiler and HTHP), this is attributed to the elimination of the local combustion process and, accordingly, the associated combustion-related emissions. In the case of hydrogen use, the possibility is seen that NO_x-emissions may increase in the short term due to higher combustion temperatures. In the longer term, however, it is expected that this can be controlled by the process. It should be remembered that

the consideration of air pollutants is limited to the steam generating unit per se, i.e. upstream and downstream steps are not considered including any off-gas post-process-treatment. For example, the combustion of hydrogen currently requires downstream waste gas after-treatments due to increased NO_x-emissions.

- **Other burdens:** No substantial changes are expected along the considered aspects. While, for example, electromagnetic fields can occur in the electrically operated boilers, these are seen as manageable based on experience from other electrical processes. Possible hazards due to the release of certain refrigerants for heat pump applications and with regard to the handling of hydrogen have also been pointed out in literature and by experts. Yet, due to safety regulations and by references to commercial installations, this is not expected to be critical.
- **Metallic resources:** No substantial changes are perceived in the demand for metallic resources, even though there are substantial uncertainties related to use of particular metals. In particular, it has been pointed out that changes in components may be possible (e.g. less steel required for electrode boiler and higher weight of heat pumps due to more metal required), however, the magnitude is not considered relevant.
- **Other resources:** Some changes for particular techniques have been identified. For example, with regard to space requirements, changes in both directions have been pointed out: According to manufacturers, an electrode boiler requires about one quarter of the size of a gas boiler and less auxiliary systems for gas and exhaust air in general, yet the installation of an electric medium voltage switch gear might be necessary. Heat pumps as tailored installation, on the contrary, might require more space. The order of magnitude is difficult to quantify, however. Hydrogen boilers without flue gas recirculation have, according to manufacturers, a loss in performance of about 10–15 %, which requires a larger dimensioning of the boiler. However, in sum, such orders of magnitude are rated as rather irrelevant in terms of overall impacts.

In contrast to these criteria, the following ones are not only mainly determined by technological properties but also by future framework conditions. They can thus not be considered as

5. According to the experts interviewed, a temperature level between 70–90 °C can be assumed for the majority of waste heat from chemical parks (assumed source temperature therefore 80 °C).

Table 4. MDA results of quantitative criteria per unit of application.

Application/ Criterion	Unit	Reference				Alternatives															
		2020	2030	2040	2050	2020				2030				2040				2050			
Paper drying		Natural gas-fired steam boiler				Electrode boiler				Heat pump system				Natural gas-fired CHP-plant				Hydrogen-fired steam boiler			
CO ₂ emissions	[kt CO ₂ /a]	68	65	65	65	+98%	-47%	-86%	-100%	-74%	-93%	-100%	-26%	+24%	+36%	+40%	-100%	-100%	-100%	-100%	
Final energy demand	[GWh/a]	244	232	232	232	-7%	-3%	-3%	-3%	-52%	-55%	-57%	+33%	+40%	+40%	+40%	-3%	-0.2%	+0%	0%	
Investment	[Mo Euro/a]	0.2	0.2	0.1	0.1	+33%	+33%	+40%	+40%	+600%	+575%	+490%	+550%	+550%	+566%	+566%	+30%	+30%	+40%	+40%	
Operational costs	[Mo Euro/a]	11.4	13.5	18.0	25.0	-16%	-28%	-45%	-60%	-57%	-69%	-78%	-6%	+7%	+15%	+22%	+33%	+12%	-14%	-38%	
Milk powder production		Natural gas-fired CHP-plant				Electrode boiler				Centralised heat pump				Decentralised heat pump				Hydrogen-fired steam boiler			
CO ₂ emissions	[kt CO ₂ /a]	25	39	43	44	+168%	-57%	-89%	-100%	-79%	-95%	-100%	-74%	-94%	-100%	-100%	-100%	-100%	-100%	-100%	
Final energy demand	[GWh/a]	153	153	153	153	-30%	-31%	-31%	-31%	-66%	-68%	-70%	-58%	-60%	-63%	-27%	-29%	-29%	-29%		
Investment	[Mo Euro/a]	0.7	0.6	0.6	0.6	-79%	-79%	-79%	-79%	+104%	+92%	+68%	+138%	+124%	+96%	+42%	+58%	+68%	+68%		
Operational costs	[Mo Euro/a]	5.8	7.6	10.5	15.1	-17%	-36%	-53%	-67%	-53%	-67%	-78%	-43%	-60%	-73%	+22%	-6%	-31%	-52%		
Chemical park steam supply		Natural gas-fired CHP-plant				Electrode boiler				Heat pump system LP &				Heat pump system LP/MP &				Hydrogen-fired steam boiler			
CO ₂ emissions	[kt CO ₂ /a]	497	820	903	934	+203%	-53%	-88%	-100%	-67%	-92%	-100%	-70%	-93%	-100%	-100%	-100%	-100%	-100%		
Final energy demand	[GWh/a]	3514	3476	3476	3476	-25%	-25%	-25%	-25%	-47%	-47%	-47%	-52%	-54%	-57%	-22%	-23%	-23%	-23%		
Investment	[Mo Euro/a]	9.7	8.7	8.2	8.2	-74%	-74%	-73%	-73%	-26%	-30%	-36%	+127%	+114%	+87%	-46%	-39%	-36%	-36%		
Operational costs	[Mo Euro/a]	102.3	140.7	208.5	313.0	+8%	-21%	-45%	-63%	-41%	-60%	-73%	-40%	-60%	-75%	+71%	+24%	-14%	-43%		

independent from the actual expectations concerning the future development and are thus subject to uncertainty. In terms of general setup, the idea of a decarbonisation to be pursued until 2050 is taken up. In turn, it is expected that there is support by society and the necessary transformation in terms of establishing renewable energies and energy infrastructures is ensured.

- Interaction:** Initially, the picture tends to be more negative for the alternative technologies, but this changes over time. With regard to lock-ins, it can be pointed out that a choice of electricity-based technologies is a commitment to electricity as an energy source. Gas- or fuel-based systems, on the contrary, can often rely on more than one energy carrier (e.g. hydrogen or natural gas). With regard to the importance of compatibility, the currently limited availability of the necessary electricity or hydrogen infrastructures has been pointed out. In particular, the origin of the hydrogen plays a decisive role and is currently not foreseeable. In the short term, this is an argument against the use of corresponding technologies; in the longer term, it is assumed that the expansion of the infrastructures would favour their use.
- Acceptance:** Here, a positive picture emerges across all technologies. With regard to technology manufacturers and users, it is expected that they are fundamentally interested in the introduction or operation of alternative, low-emission technologies as a new market - as far as the operation is economically feasible and the necessary infrastructures are available. By definition, the external energy supply including its infrastructures lies outside the system boundary. Accordingly, the attitude towards the transformation of the general external infrastructure for generation capacities and energy transport necessary for energy supply is not included here, but may play an important role.
- Competitiveness and value-added:** Again, a positive trend is found across all technologies. Areas with changes include R&D activities, technology leadership and synergies with other areas in line with the general trend towards low-emission technologies. An increase in current R&D is expected as the economic relevance increases and, according to the expectations, this could also have a positive impact on technology leadership.

Quantitative criteria

Table 4 shows the results of the quantitative criteria. For the reference technique, the quantitative results per application are given as absolute values. The values for the corresponding alternative techniques are indicated as changes in percent relative to the reference. The values refer to one “steam generating unit” of the application. For the chemical park, for example, the “steam generating unit” represents its entire steam supply that consists of several individual boilers within a CHP-plant. A colour scale from green to red simplifies the comparison of alternative techniques within an application.

As pointed out in the methodology, the results are based on the assumption of a gradual decarbonisation and phase-out of fossil fuels until 2050. This is reflected in reductions of GHG emissions of the alternative technologies by 100 % in 2050 compared to the reference technology.

Looking at the development of the respective reference technique, it should be noted that a CHP system is defined as reference for the chemical park and milk powder application, while a natural gas boiler is defined as reference for paper drying.⁶ To enable comparability of the resulting GHG emissions (and their costs), CHP plants receive credits for the avoided GHG emissions of the electricity not drawn from the grid in comparison with natural gas boilers. As a result, the net GHG emissions of CHP plants increase as the decarbonisation of the electricity grid progresses. The same applies to the operational costs of CHP plants, which also depend heavily on revenue generated through avoided grid purchases considered here by lower energy costs. In parameter sets that achieve decarbonisation by 2050, a significantly lower electricity price is assumed, which has a strong negative impact on the economic viability of CHP over time, as can be seen in the direct comparison with a natural gas boiler as in the paper drying application.

When comparing the respective alternative techniques with their reference, it can be noticed that the results tend to be quite similar for the electrode boilers, HTHP systems and hydrogen boilers, regardless of the specific application. Nevertheless, some key tendencies can be summarised as follows under the framework data and assumptions made:

6. A CHP is included as a fossil alternative, as internal steam and energy supply is traditionally a core business of the paper industry. It is assumed that about half of the current plant stock consists of natural gas boilers and the other half of CHP plants.

- **Greenhouse gas emissions:** In the case of electricity-based technologies (i.e. electrode boiler and HTHP), it can be observed that there is an initial increase in emissions in 2020 as compared to the reference. Later, this turns into an overall reduction in the following decades. This can be explained by the expectation of a transition from a fossil-based electricity mix in the short term to a renewable-based electricity mix in the long term. Assuming that renewable hydrogen is used in the hydrogen boiler, this technique is already CO₂-neutral in 2020.⁷ Also, depending on which reference technique is used - natural gas boiler or CHP - the change in emissions of the alternative technologies varies, especially in 2020.
- **Final energy demand:** The development of final energy demand is directly related to the assumed efficiencies of the respective techniques (see application section and Table 2⁸) and the expected efficiency improvements over time. In general, the demand of all alternative techniques shows a relative decrease compared to the reference. However, heat pumps are by far the most efficient alternative. Depending on the chosen reference technique, i.e. natural gas boiler or CHP, the reduction in energy demand varies, as CHP requires more fuel for the same amount of steam, but also provides electricity, in addition.
- **Investment:** The investments vary substantially depending on the respective technique (also see Table 2) and application. Among the alternative techniques considered, heat pumps require the highest investments as compared to the other techniques. Obviously, the change in investment again depends on the chosen reference, i.e. natural gas boiler or CHP, as the CHP plant requires higher investment than the natural gas boiler.
- **Operational costs:** The criterion describes the annual change in all running costs (including energy, CO₂, operating and maintenance costs) due to the conversion of the reference technologies to the alternative technologies. As shown in Rehfeldt et al. (2021), the operational costs are largely determined by the energy and CO₂ prices, while investment as well as operating and maintenance costs play a very subordinate role. To enable a market-based shift to CO₂-neutral steam generation, the most important measures are therefore a significant reduction in the price of electricity (to about €40/MWh) and a simultaneous increase in the CO₂ price (to over €200/t) (Rehfeldt et al. 2021). Under these assumptions, Table 4 shows how natural gas is becoming increasingly unattractive. As electricity prices fall, direct-electric alternative techniques such as HTHP and electrode boiler become more attractive. They also benefit because direct expenditures for CO₂ allowances are assumed to be “passed on” to electric utilities. It can be observed that the hydrogen boiler is initially dominated by high energy prices for hydrogen; only strong price signals will make it more attractive by 2050.

7. The hydrogen production itself is outside the scope of consideration, but the model optionally allows the use of electricity-mix hydrogen.

8. For the CHP plant, an efficiency of 0.9 and a power to heat ratio of 0.3 are assumed (Suhr et al. 2015). The assumed invest is €1300/kW_e (Danish Energy Agency and Energinet 2020; Prognos AG 2014).

Discussion

Compared to the current state-of-the art, which electricity-based technologies are available for steam generation and what is their development status?

The provision of thermal energy in the form of process steam at a temperature level below 500 °C plays an important role as a cross-cutting technology. State-of-the art technologies are steam boilers and CHP plants based on the combustion of natural gas (exemplified by three applications from paper, food and chemical industry considered in this study). For a long-term switch to CO₂-neutral steam generation, there are various alternative technologies based on direct electrification or hydrogen combustion. According to literature and interviews, the most promising ones include electrode boilers, heat pumps and hydrogen-fired steam boilers. Their use is conceivable both individually and in combination as in the applications. H₂-ready boilers that can be easily converted from natural gas to hydrogen, could be an attractive transitional solution.

The results indicate that the degree of technological readiness of the alternatives considered varies. According to the manufacturers interviewed, electricity-based and hydrogen-fired boilers are available for large-scale use, with electrode boilers already being used as a standard product in the balancing power market, while high-temperature heat pumps for steam generation are still hardly widespread. The required high steam pressures and temperatures as well as large connected loads of up to several hundred megawatts require further research and development in the field of HTHP. In addition, market barriers to the further diffusion in industry need to be overcome. First and foremost as stated in Arpagaus et al. (2018), the limited experience in integrating HTHP into industrial processes, the further development and widespread use of high-temperature refrigerants with low GWP (also considering safety, efficiency and availability criteria) and the high price ratio of electricity to fossil fuels play an important role. Yet, the potential of this technology is considerable (Nellissen, P. Wolf, S. 2015), especially in food and paper industry where process heat is mostly required below 200 °C, and for low-pressure steam in chemical parks. The interview results suggest, that the wide-spread application of hydrogen- or electricity-based systems for steam generation largely depends on the infrastructure provided (possibly with storage options), the expansion of renewable energies and the economic viability of such systems. As a precaution against the high price spread per kWh between natural gas and electricity, hybrid systems can represent a transitional solution.

How are these technologies alternatives evaluated compared to the current fossil reference technologies from a multi-dimensional perspective?

The results for the 11 MDA criteria are similar across all three applications under the exemplary framework conditions. The MDA does not reveal any fundamental reasons that appear to stand against a widespread use of particular alternative technologies. Assuming that decarbonisation is successfully pursued until 2050, a switch to electricity-based steam technologies is the logical consequence. From an ecological point of view, next to a reduction in **GHG emissions**, an improvement in the release of **air pollutants** is also expected, particularly via a change from fossil

combustion towards electrode boilers and heat pumps. Across applications, no relevant **burdens** could be identified under the premise of compliance with necessary safety precautions; potential accidents tend to be limited to the local environment. Substantial changes in the demand for **metallic resources** have also not been identified, but shifts within the metal used are conceivable. Likewise, no particularly critical issues are perceived concerning **other resources**. However, local space conditions must be taken into account for individual solutions. Furthermore, depending on the process, upstream and downstream plants, as well as auxiliary units are affected by a changeover. From a technological point of view, the final **energy demand** would significantly be reduced in case of switching to heat pumps. For the other alternative techniques considered, only a minor change in final energy demand is to be expected. With regard to **interactions**, lock-in effects due to the electrification have been mentioned, since in principle no alternative energy carriers can be used as a substitute for technologies with a direct electric heating system. At the same time, the availability of the necessary electricity and hydrogen infrastructure is an important aspect for a successful diffusion. No problematic aspects were identified for the criterion of **acceptance**, although appropriate infrastructure is needed and the economic conditions must generally be favourable. From an economic point of view, **investments** for the alternative techniques are either higher or lower than for the reference, depending on the technology, but they also strongly depend on the system boundaries. Yet, it is also important to note that investment only plays a minor role compared to **operational costs**, which are strongly dominated by energy cost. If electricity prices decline, direct-electric alternatives become more attractive, while a conversion to hydrogen is unprofitable from an economic point of view under the predicted hydrogen prices. In the upstream diffusion model a significant reduction in the price of electricity (to about €40/MWh) and a simultaneous increase in the CO₂ price (to over €200/t) enable a market-based shift to CO₂-neutral steam generation by 2050 (Rehfeldt et al. 2021). Assuming a general development towards low-emission technologies, a positive contribution to **competitiveness** is seen in connection with the conversion.

With regard to the interpretation of the findings, general **limitations** of interview approaches apply (Yin 2009). Furthermore, the summarised key statements in this section cannot be made independently of the assumption of certain framework conditions. The remaining qualitative criteria, especially those of non-technical origin, cannot be classified independently of the assumed framework conditions either. It is assumed, for example, that decarbonisation will be driven forward and supported by society, and that the necessary expansion of renewable energies and energy infrastructures will also take place. And finally, in terms of methodology, pairwise comparison are helpful to obtain clear distinctions between two alternatives, yet the selection of a reference technique is not always unambiguous. Thus, it is important to keep information on the underlying techniques in mind.

Conclusions

The aim of this paper was to investigate on alternate options for decarbonizing steam-generation and to review them from a multi-dimensional perspective. For this purpose, three steam-

applications in the paper, food and chemical industries are investigated. They serve as examples for a holistic assessment of CO₂-neutral steam generation using an MDA. In the MDA, innovative alternatives currently under development are compared to state-of-the art reference techniques mostly based on fossil fuels. More specifically, electrode boilers, heat pumps and hydrogen-fired steam boilers are analysed along 11 ecological, economic and technical criteria for the example of Germany based on data from a literature review, interviews with 19 experts and by applying a quantitative model.

Based on the results of this investigation, the pivotal question about the future of steam generation can be answered as follows: There are technologies (electrode boilers, heat pumps, hydrogen-fired steam boilers) that allow a long-term decarbonisation of steam-generation by 2050. However, it becomes clear that introducing these technologies in the shorter term may initially be associated with rising emissions and costs. Yet with a perspective towards decarbonisation, it might also be necessary to avoid lock-ins into fossil fuels due to the long lifetimes of new installations. Yet the specific results also depend strongly on the chosen reference and the assumed framework conditions. It can be noted that the results tend to be rather similar across the different applications investigated in the MDA. This suggests that, on an aggregate level, the steam sector might be assessed independently of specific applications.

In sum, the analysis does not reveal any fundamental reasons that seem to impede a widespread use of alternative technologies for steam generation. From the point of the ecological criteria other than GHG emissions, additional space requirements, safety precautions or auxiliary systems required may need to be given consideration in the choice of technique. From a technological point of view, heat pumps - where applicable - have a relevant efficiency advantage that usually makes them more attractive than electrode or hydrogen boilers. Yet, with a view to the future use of the technologies, continuous research and development activities are required to bring HTHP to market maturity, while electrode and hydrogen boilers are already available for large-scale use. From an economical point of view, a decisive factor for the use of alternative technologies remains their cost-effectiveness. As shown in Rehfeldt et al. (2021), energy costs (compared to other cost components) have a decisive impact here. When drawing up a development strategy for electricity-based technologies, it must also be carefully examined how a reliable supply of electricity can be ensured in view of increasing energy demand and higher shares of fluctuating renewable energies. For the successful industrial use of alternative technologies, policy making will have to ensure competitive economic as well as ecological and infrastructural framework conditions with a long-term perspective.

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