

PRELIMINARY IMPACT ASSESSMENT OF AN INNOVATIVE NEAR-ZERO EMISSIONS BIOMASS ENERGY SUPPLY SYSTEM

Birte Schnurr^{1}, tel: +49 202 2492-314; e-mail: birte.schnurr@wupperinst.org*

Thomas Götz¹, Jan Kaselofsky¹, Ingwald Obernberger², Thomas Brunner²,

Antonia Horn², Khaled Osman³

*¹⁾ Wuppertal Institute for Climate, Environment and Energy,
Doeppersberg 19, 42103 Wuppertal, Germany*

²⁾ BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

³⁾ Utrecht University, Utrecht, the Netherlands

ABSTRACT

Biomass is an important renewable alternative to fossil energy sources for process heat generation in industrial applications. The Horizon Europe project CBE4I - Clean Bioenergy for Industry (Grant Agreement No. 101122292, Duration: 09/2023 - 08/2026, coordinator: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria) aims to develop a novel highly efficient biomass-based process heat supply system using an updraft gasifier combined with advanced gas cleaning systems and other innovative energy solutions, including a heat pump for flue gas heat recovery. This system operates with near-zero air emissions of dust and other air pollutants, significantly outperforming existing biomass technologies while providing a low carbon transition option for industrial applications. This paper presents results from the initial phase of the project, including preliminary technology performance data from early development stages and initial techno-economic analyses. These results, together with an in-house developed stock model, form the basis for a preliminary impact assessment considering different deployment scenarios and analysing the potential of the new technology to reduce emissions and support the EU's climate and clean air objectives, including the increased use of renewable energy. The results will contribute to the further refinement of the technology and support discussions on future policy development.

Keywords: environmental impact assessment, efficient biomass gasification and combustion technology, industrial applications, renewable energy sources

Introduction

The European Union has set ambitious climate and clean air targets. The Green Deal, announced in December 2019, aims to reduce greenhouse gas emissions by 55% compared to 1990 levels by 2030. It also establishes air quality standards based on the World Health Organization's (WHO) recommendations (European Commission, 2019). Similarly, the recast Ambient Air Quality Directive (EU) 2024/2881 aims to reduce the health impacts of air pollution by more than 55% and the number of EU ecosystems where biodiversity is threatened by air pollution by 25% by 2030 (European Commission, 2024). The updated WHO air quality guidelines also lowered maximum levels for particulate matter and nitrogen dioxide (World Health Organization, 2021). Altogether, the European Union is pursuing a zero-pollution vision for 2050, so besides ambitious GHG emission reduction goals, clear air quality standards for 2030 and beyond are set.

Furthermore, following the Russian invasion of Ukraine, the Commission published the REPowerEU plan in May 2022, with the aim of achieving greater independence for the EU from Russian oil and gas imports (European Commission, 2022). In the revision of the previous Renewable Energy Directive (RED II), the EU's binding overall renewable energy target of 32% by 2030 was increased to a minimum of 42.5% in the current RED III, with an additional 2.5% target to reach 45% (European Commission, 2018b, 2023b). An accelerated expansion of wind and solar energy are the key strategies to realise this more ambitious target, although for the respective energy sources, no sub-targets are specified. A requirement for biomethane is however formulated, aiming for an increased sustainable production within the EU of 35 billion cubic metres by 2030 at the latest. The Green Deal sets a continuous increase in the share of renewables in industry of 1.6% per year, with a phased sub-target for the heating and cooling sector of 0.8% per year by 2026 and 1.1% by 2030 (European Commission, 2022).

To provide process heat for a low carbon industry, biomass is considered by the EU to be a suitable fuel as it is both renewable and seen as carbon neutral, so there is often an intention to expand the use of biomass. In fact, when biomass is burned, only the amount of carbon previously absorbed by the plants is released, so there is an overall mathematical balance. That way, biomass combustion reduces greenhouse gas emissions by up to 90% compared to natural gas as shown in the results section (Figure 11). However, there is an ongoing scientific and political debate on the issue of allocation, which will not be explored in this paper, but a brief overview will be given. The core of the debate lies in the different periods of uptake and release considered. While forest growth can reduce atmospheric CO₂ emissions, catastrophic events such as parasites or natural disasters, as well as a deterioration in the general condition of the forest, can turn even a natural forest from a supposed sink into a source of CO₂ emissions. For this reason, recent studies indicate that only additional sequestration of active carbon and geological storage of emissions will be long-term sinks for reducing greenhouse gas concentrations in the atmosphere, otherwise a further increase in global average temperature is expected (Allen et al., 2025; Chatham House, 2022; Denvir & Leslie-Bole, 2025; Harrison, 2025).

Notwithstanding this discussion, projections based on the RED II target for the share of renewables in the Green-X EUCO27 scenario developed for the European Commission show an increase in biomass heat production to 104 Mtoe and biomass electricity generation to 24 Mtoe in 2030. These figures compare to 80 Mtoe of biomass heat production and 14 Mtoe of biomass electricity generation in 2014 (VITO et al., 2017). A remaining challenge are the relatively high emission levels of particulate matter of different size (total suspended particles, TSP), nitrogen oxides (NO_x) and carbon monoxide (CO) from conventional biomass boiler systems, cf. Figure 12. Therefore, extended use of biomass combustion without technological innovations, such as the CBE4I system, would be contrary to the objectives of the revised Air Quality Directive and the REPowerEU plan (European Commission, 2022, 2024). In addition, the supply of truly sustainable biomass is very limited. This is particularly the case if competition with agricultural production is to be avoided, and if dependency on imports - which also exists in this area - is to be eliminated. This issue is addressed in the Union Bioenergy Sustainability Report (European Commission, 2023c). It is therefore essential to maximise energy efficiency while reducing air pollutant emissions from combustion when using biomass to replace fossil fuels in industry in order to avoid greenhouse gas emissions.

To address these issues, the EU's Horizon Europe programme is supporting projects to develop innovative systems for clean biomass process heat generation. At the heart of these efforts is the Horizon Europe project CBE4I – Clean bioenergy for industry. The capacity of a typical real-scale CBE4I plant is 5 MW (fuel power) at nominal load, resulting in an annual fuel demand of 30 000 MWh and an annual heat production of 34 475 MWh. An overview and process scheme of the CBE4I system is shown in Figure 1 below.

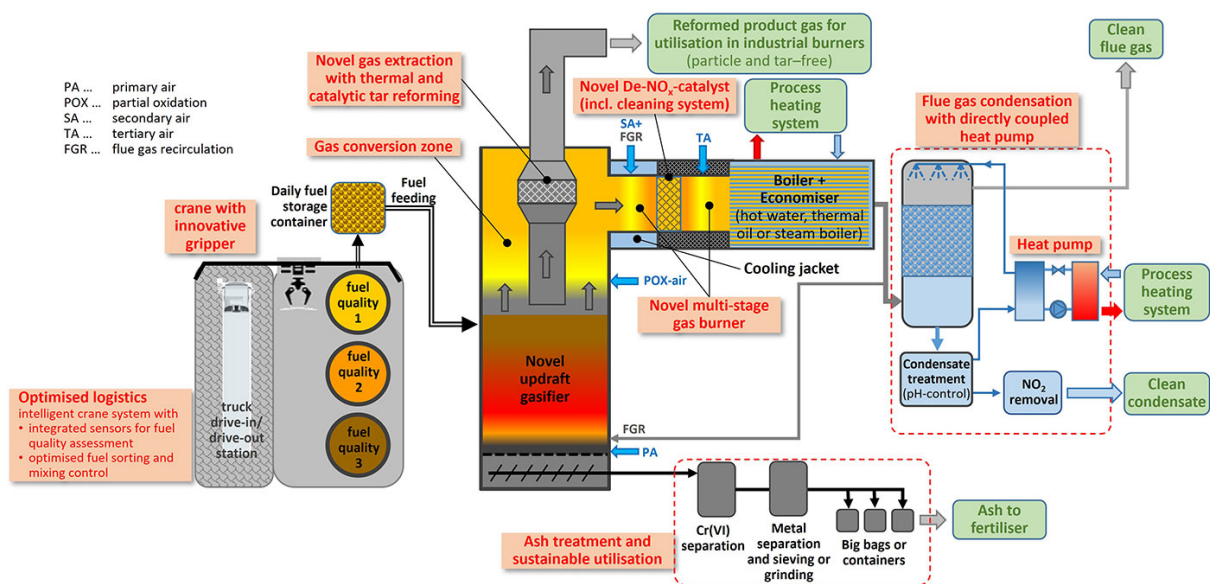


Figure 1. Process scheme of the CBE4I system (BIOS Bioenergiesysteme GmbH, 2025). *Source:* Own illustration by the CBE4I consortium (<https://cbe4i.eu/project>)

The gas extraction module contains thermal and catalytic tar reformers, so the reformed product gas for utilisation in industrial burners is almost particle and tar-free. The remaining gas is burned in a two-stage gas burner, where a three-way catalyst is installed between the combustion stages to reduce NO_x emissions. In the flue gas condensation unit, the condensate is treated to neutralise acid flue gas components like sulphates and HCl with NaOH and finally remove NO_2 . The direct coupling with a heat pump in this unit allows an overall thermal system efficiency up to 111% (related to the net calorific value (NCV) of the fuel), significantly outperforming existing biomass technologies in both efficiency and emission levels. Thanks to the extensive gas treatment described above, the CBE4I system shall distinguish itself from current state-of-the-art systems by virtually zero emissions of CO , non-methane volatile organic compounds (NMVOC), dust and significantly reduced NO_x emissions. Furthermore, the system is aimed to be waste-free as the ash is treated to be used as a biomass ash-based fertiliser. The aim is to close both the CO_2 cycle and the mineral cycle in order to achieve the sustainable use of biomass residues for energy and materials. In this way, the system will help exploit the significant energy potential of biomass residues while reducing the carbon footprint of industrial heat production and contributing to the EU's climate, clean air and circular economy targets.

The project methodology incorporates technology development, risk and techno-economic evaluations, market research and environmental impact assessments, alongside targeted dissemination activities. This paper presents the results of the preliminary impact assessment, which are based on technology performance data from the early stages of development and initial techno-economic and market analyses. These findings form the basis for analysing the potential of the new technology to reduce emissions and support EU climate objectives. They will contribute to the further refinement of the technology as well as support further discussions on policy development. For the purposes of the preliminary impact assessment presented in this paper, a stock model developed in-house by the Wuppertal Institute was used to carry out a scenario analysis considering different deployment scenarios. The methodology is explained in more detail later in this paper.

OBJECTIVES

The preliminary impact assessment presented in this paper analyses the potential environmental and major economic impacts of the introduction of the new CBE4I system compared to the use of state-of-the-art biomass systems or natural gas boilers on Austrian and German greenhouse gas (GHG) emissions and air pollutant emissions (CO, NMVOC, NO_x and TSP), using the pulp and paper and dairy industries as examples. In addition, the fuel and grid electricity consumption of the evaluated systems will be quantified and compared, which is relevant in the context of the sustainable biomass potential in the EU and the national grid capacities to meet the targets and criteria of the REPowerEU plan and the Renewable Energy Directive (European Commission, 2022, 2023b). The diversification of energy sources and switching to domestically generated renewable fuels for the sake of supply security were already part of the 2014 European Energy Security Strategy, developed after Russia's unlawful annexation of Crimea. The CBE4I system's ability to use different biomass fuels and even low-value residues therefore potentially contributes to both national and European energy security. Furthermore, using low-value residues can reduce competition for resources while operating within a closed CO₂ and mineral cycle with fuels that meet all sustainability criteria.

The CBE4I project generally adopts a two-phase approach to all analyses. This paper presents the preliminary assessment, which is based on the initial data collected during the first project phase. A final assessment will follow, incorporating additional data from manufacturing partners as the project progresses. To compare the CBE4I system with two alternatives of state-of-the-art technology, data from the preliminary techno-economic analysis conducted by the project coordinator, BIOS, has been used.

METHODOLOGY

The methodology used to prepare the impact assessment is derived from the Impact Assessment Guidelines of the European Commission (European Commission, 2009, 2021). The project consortium has selected the pulp and paper industry (A) and the dairy industry (B) in Austria and Germany respectively as two representative industry sub-sector to be analysed. Specifically, application case A1 involves heat generation only using the CBE4I system within the pulp and paper sector, while application case B1 applies the same system setting to the dairy sector. In this paper, while the sales and stock development are presented for different biomass deployment scenarios in both countries, the total emissions and total costs shown refer to the pulp and paper industry in Germany solely, assuming that biomass is used to supply the entire heat demand in the industry sub-sector.

In terms of industry-wide heat demand, the pulp and paper sector in Austria accounts for approximately 20% of the country's total industrial heat consumption, equating to around 70 000 TJ annually. In Germany, this figure is about 10%, or roughly 190 000 TJ per year. Currently, biofuels and waste cover about 50% of this demand in Austria and about 20% in Germany. For the dairy industry (B), the share of total industrial heat demand is lower, amounting to about 0.1% in Austria (2 000 TJ) and 1% in Germany (30 000 TJ). Biofuels and waste already account for about 25% of this demand in Austria and about 16% in Germany. In terms of temperature requirements, more than 90% of the heat demand of the pulp and paper industry (A) in both countries is in the 100-200°C range. In contrast, in the dairy sector (B) more than 90% of the heat demand is at temperatures up to 100°C (Kermeli & Crijns-Graus, 2020b).

For the comparative analysis in this preliminary impact assessment, three different technological solutions for addressing the heat demand are regarded, which are detailed below. To ensure that system performance is comparable, alternative systems are assumed to have identical nominal heating capacities and the same number of operating hours at full load per year. As a result, all systems produce the same annual heat output of 34 475 MWh, assuming 6 000 hours of full load operation.

The selected technology options include:

- **CBE4I using biomass (CBE4I):** Novel fuel-flexible biomass gasification-based technology, running on wood chips in the preliminary assessment, with gas cleaning (three-way catalyst for NO_x emission reduction) and flue gas condensation with a directly coupled heat pump and condensate treatment.
- **Boiler using biomass with flue gas condensation and heat pump (Biomass_boiler):** Traditional biomass boiler running on wood chips, coupled with state-of-the-art flue gas condensation combined with a heat pump.
- **Boiler using natural gas (Gas_boiler):** Traditional natural gas boiler without flue gas condensation.

Sales and stock modelling

The Wuppertal Institute calibrated its proprietary sales and stock model using input data on the development of heat demand in the respective industrial sectors in Germany and Austria, provided by project partner Utrecht University. This data was used as an upper limit of the market potential. The work of Utrecht University encompassed defining the framework and diffusion scenarios for the innovative technology, in addition to modelling the generic logistic growth function for its diffusion. The framework scenarios include the EU reference scenario and a frozen efficiency scenario, within which the three different technology deployment scenarios are considered (Kermeli & Crijns-Graus, 2020a). At the Wuppertal Institute, this preliminary work was used to model the annual sales figures for CBE4I technology and the resulting stock development (total number of systems installed), using the EU reference scenario as the general framework for the three diffusion scenarios described below:

- 1) By 2050, biomass supplies the entire heat demand in the industry sub-sector, now supplied by several sources (coal and coal products, oil products, natural gas, nuclear, hydro, geothermal, solar/wind/other biofuels and waste heat).
- 2) By 2050, biomass supplies the heat demand of the industry sub-sector currently supplied by fossil resources (coal, oil and natural gas).
- 3) The diffusion of CBE4I technology is limited to the biomass segment, without a switch from other energy sources to biomass.

As is typically the case in market analysis, it is assumed that the diffusion of the new technology will follow a logistic growth curve with a threshold value, or 'carrying capacity', which is derived from the projected heat demand and a defined growth rate. Based on these assumptions, market projections are made using the standard logistic growth function provided by project partner Utrecht University:

$$\text{Sales diffusion (t)} = \frac{K}{1 + e^{-b(t-t_0)}}$$

Equation. 1

In this equation, K represents the carrying capacity, or market potential, in 2050; b represents the growth rate; and t_0 represents the inflection point, or the year with the highest diffusion rate. A typical range for growth rates in logistic models is between 0.1 and 1.0, so $b = 0.5$ was chosen. Similarly, as a reasonable initial guess, $t_0 = 2040$ as the midpoint of the time range was chosen. With these assumptions, the equation becomes:

$$\text{Sales diffusion (t)} = \frac{K}{1 + e^{-0.5(t-2040)}}$$

Equation. 2

The applied logistic growth function is illustrated in Figure 2.

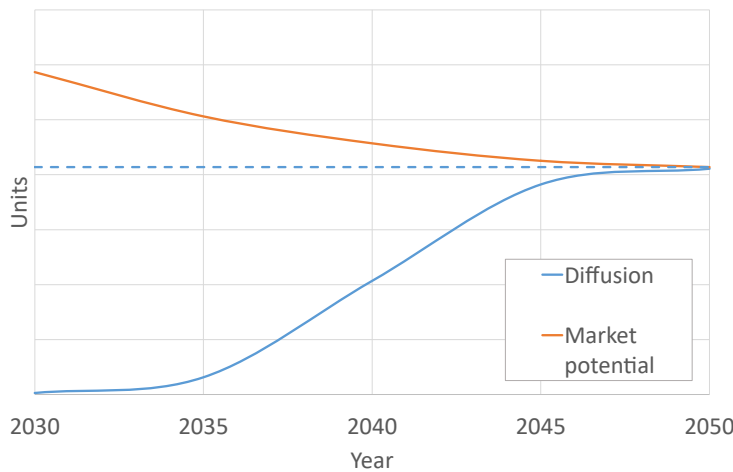


Figure 2. Qualitative illustration of the assumed CBE4I technology diffusion in the industrial biomass heating market
Source: Own illustration, function modelling from input by project partner Utrecht University

The sales development in Germany and Austria can now be modelled for the three aforementioned roll-out scenarios (see Figure 3). The annual sales t translate the projected future demand potentially served by the CBE4I system into the technical sales potential for the whole market segment. It is assumed that all technology alternatives have the same stock of units, which is calculated for each year t using the formula:

$$\text{stock}_{i,t} = \text{stock}_{i,t-1} + \text{sales}_{i,t-1} - \text{sales}_{i,t-T-1},$$

Equation. 3

In this equation, i refers to the application case and T signifies the technical lifetime. For all three systems, a technical lifetime T of 20 years is taken from the techno-economic analysis by project coordinator BIOS, while considering that single components such as the catalysts and the heat pump require earlier replacement. Furthermore, it is assumed that additional sales corresponding to the projected demand result from the decommissioning of End-of-Life units and their replacement.

As a result of improved efficiency and ongoing decarbonisation initiatives, the EU reference scenario projects a decline in the overall heat demand of the pulp and paper industry by 2050, with a particular reduction in the reliance on fossil energy sources such as coal, oil, and natural gas. This trend toward greater energy efficiency is also reflected in a gradual decrease in sales figures over time, which becomes especially noticeable in Scenario 1 for Germany after 2040.

Between 2020 and 2025, a significant drop in heat demand has already led to lower sales (not depicted in the results figure below but incorporated as input data from project partner Utrecht University). Consequently, fewer End-of-Life units will need replacement beyond 2040.

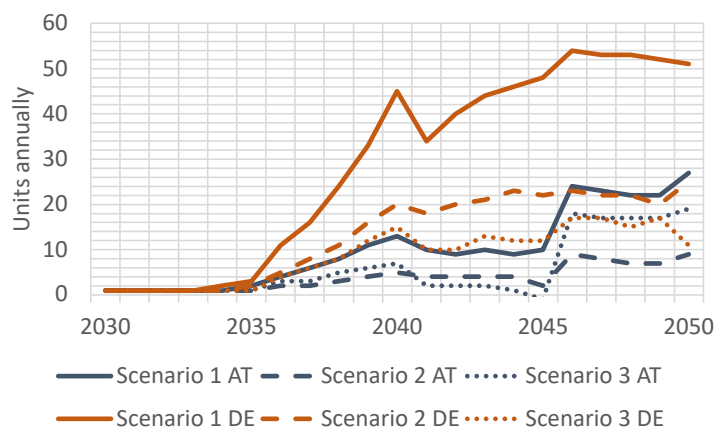


Figure 3. Sales development of 5 MW units in Germany (DE) and Austria (AT) for application case A1 (pulp and paper industry, without product gas extraction) and the three different scenarios, under the preconditions of the EU reference scenario for energy efficiency and market trends

In all three deployment scenarios, the overall share of fossil fuels is expected to decrease over time, while the use of biomass increases. As a result, Scenario 3 shows higher sales figures than Scenario 2 in Austria from 2045 onwards (including the replacement of end-of-life plants), as biomass already has a strong market presence in Austria even before the introduction of CBE4I technology. However, between 2049 and 2050, different trends emerge between Scenario 3 and the two countries. In Austria, the share of biomass in the pulp and paper industry's heat supply continues to grow, whereas in Germany, projections indicate a temporary slight decline in biomass share between 2045 and 2050. This trend stems from projected heat demand, prior market developments, and the replacement of End-of-Life systems. Overall, sales figures remain moderate in all scenarios. Scenario 1 in Germany stands out with significantly higher sales, reaching up to 54 units per year, while the other scenarios range between 10 and 30 units annually. In Austria, absolute figures remain low, making the variation between scenarios appear moderate. However, in the larger German market, these differences are more pronounced.

According to preliminary data from project partner Utrecht University, the heat demand in the dairy industry is considerably lower than in the pulp and paper sector, leading to lower sales figures (not depicted here). This trend applies to both Austria and Germany, though it is particularly evident in Austria. The stock model used by the Wuppertal Institute uses integer values for sales figures, which can lead to rounding differences for very small numbers. Consequently, even in the most ambitious Austrian scenario, sales in the dairy sector fluctuate between one unit and none, while the other two scenarios occasionally show higher values. These variations should not be over-interpreted as they reflect the limitations of modelling very small numbers of annual installations. Similarly, breaking down figures by temperature levels would introduce further rounding-induced variations with significant impact. For this reason, no differentiation by temperature was made in the sales modelling at this stage, despite the fact that approximately 10% of the dairy industry's demand is for steam.

To generate quantitatively interpretable results in view of the relatively low sales figures in these industry sectors, the most ambitious scenario 1 was selected in the preliminary assessment for modelling stock development (see Figure 4). It is important to emphasise that this analysis focuses exclusively on Germany and Austria. Although the sales figures for these two countries may appear modest, they represent a significant market potential for CBE4I systems in the wider European context.

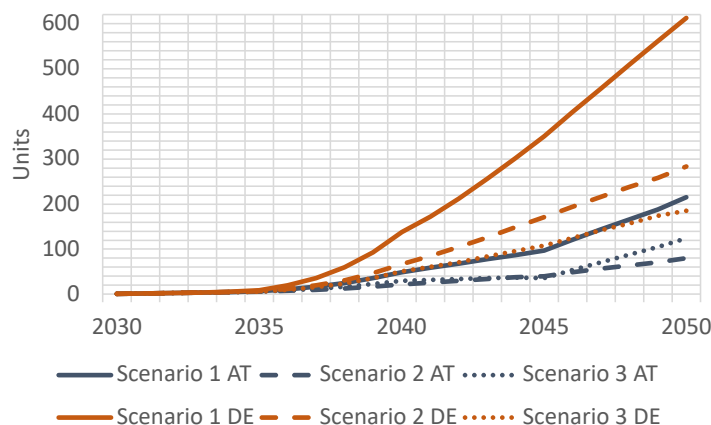


Figure 4. Stock development of 5 MW units in Germany (DE) and Austria (AT) for the pulp and paper industry, without product gas extraction, and the three different deployment scenarios, under the preconditions of the EU reference scenario for energy efficiency and market trends

Similarly, the maximum scenario 1 was chosen for the dairy sector in the preliminary assessment in order to model the development of the installed base and generate quantitatively interpretable results, given the relatively low sales figures. By 2050, a total of 15 CBE4I units are expected to be installed in this sector in Austria, while almost 100 units are expected to be in operation in the dairy sector in Germany (not shown here). To achieve the objectives outlined in the previous section, the impact assessment model generates several key outputs for each year t up to 2050, across all technology scenarios and application cases, including:

- GHG emissions in CO₂eq/year resulting from fuel and grid electricity consumption, respectively
- TSP, CO, NMVOC and NO_x emissions resulting from fuel and grid electricity consumption, respectively
- Fuel and grid electricity consumption

Although the three technology alternatives maintain the same annual heat output and full-load hours, their differing efficiencies and system components lead to variations in fuel and grid electricity demand. Based on these consumption figures, the impact assessment model calculates greenhouse gas and air pollutant emissions using emission intensities obtained from the techno-economic analysis as well as relevant literature sources.

The greenhouse gas emission intensities for fuels account for life cycle emissions. For grid electricity, the emission intensity and its projected development over time are based on the PRIMES Reference Scenario REF2020, which anticipates a decline in emission intensity in the future (E3Modelling, 2021).

Energy and CO₂ price development

The total cost of each technology option includes investment, installation, maintenance and running costs. The latter include fuel costs, which are by far the largest item, grid electricity costs, which make up most of the rest, and other consumables. In the preliminary techno-economic assessment by BIOS, the costs of replacing the catalysts are partially counted as maintenance costs and as re-investment, where the costs for new precious metals can significantly be reduced by recycling the used ones. The economic data provided by project coordinator BIOS is used as input in this preliminary impact assessment. Investment costs include only the cost of machinery and maintenance costs include operating costs other than fuel or grid electricity (including other consumables). Due to the limitations of this preliminary impact assessment, it is assumed that the prices of goods

and services will remain unchanged over time. For simplicity, any price increases, such as those due to inflation, are assumed to be offset by greater efficiency and economies of scale in production.

The prices for wood chips stem from the techno-economic analysis by BIOS or additional literature and are net of VAT (C.A.R.M.E.N. e.V., 2024). In the case of natural gas and electricity, the country-specific average of the semesterly prices for the year 2023 for non-household consumers excluding VAT and other recoverable taxes and levies¹ published by Eurostat is used as starting point (Eurostat, 2024). Between 2023 and 2050, it is assumed that gas prices for non-household consumers develop in line with the relative evolution of the EU wholesale gas price in the Announced Pledges Scenario (APS) published by the International Energy Agency (IEA) in the World Energy Outlook (WEO) 2024 (World Energy Outlook 2024, 2024). The IEA WEO 2024 APS includes all recent major announcements of national governments as of the end of August 2024, both 2030 targets and longer-term net zero or carbon neutrality pledges.

Future developments of wood chips prices are based on the 2024 recommendation of the "Greenhouse Gas Projections 2024 for Germany" and, in the case of electricity, the "Socio-economic Impact Assessment of the 2023 Projection Report" prepared for the German Federal Environment Agency (UBA) (Mendelevitch et al., 2024; Schumacher et al., 2024).

Furthermore, the future development of carbon prices is based on the assumptions in Mendelevitch et al. (2024). It is assumed that the biomass utilised in the CBE4I and biomass plants is not subject to carbon prices in accordance with Article 38 of the Regulation on the monitoring and reporting of greenhouse gas emissions (EU/2018/2066) (European Commission, 2018a). Furthermore, it is presumed that the natural gas boiler is not subject to the EU ETS due to its fuel power input of only 5 MW. However, carbon prices for natural gas consumption will apply due to the current (2025) national policies in Austria and Germany and, from 2027 on, as a result of the expected EU ETS 2. Until 2026, country-specific carbon prices are used as far as required by national legislation in Austria and Germany. As EU carbon prices in sectors not covered by the EU ETS are to be harmonised after 2027 through the introduction of a separate emissions trading system (EU ETS 2), a similar carbon price is assumed for Austria and Germany for future projections.

Figure 5 shows the assumed development of the energy prices in Germany and Austria in €₂₀₂₃ for the period 2030 to 2050.

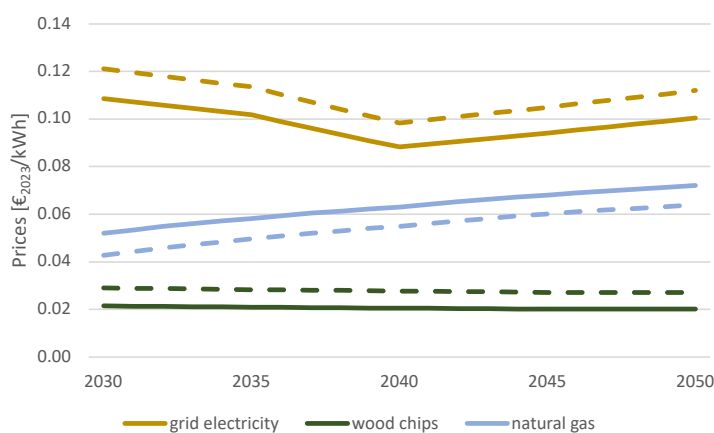


Figure 5. Assumed development of total prices of energy carriers in Germany (solid lines) and Austria (dashed lines), including CO₂-prices for natural gas

Based on the sources and assumptions used (as stated above), the price of grid electricity is assumed to decrease in real terms until 2040 and to rise from then on. Also based on the sources and assumptions used

¹ Data code nrg_pc_203 and band I4 (100,000 GJ to 999,999 GJ) in the case of natural gas and data code nrg_pc_205 and band ID (2,000 MWh to 19,999 MWh) in the case of electricity.

above, a significant increase in the total real price of natural gas is projected, mainly as a result of rising CO₂ prices. The price of wood chips is assumed to remain roughly constant in real terms.

The assumed evolution of the total natural gas price and its specific components is shown in Figure 6 for Germany and in Figure 7 for Austria. Based on the assumptions for the future development of the carbon price in Mendelevitch et al. (2024), rising CO₂ prices would more than offset the decline in EU wholesale gas prices as expected in the AP scenario of the IEA World Energy Outlook (2024).

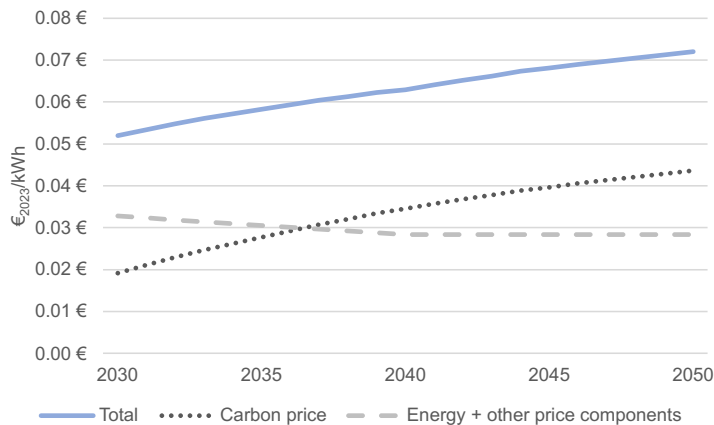


Figure 6. Assumed development of natural gas price and its components in Germany

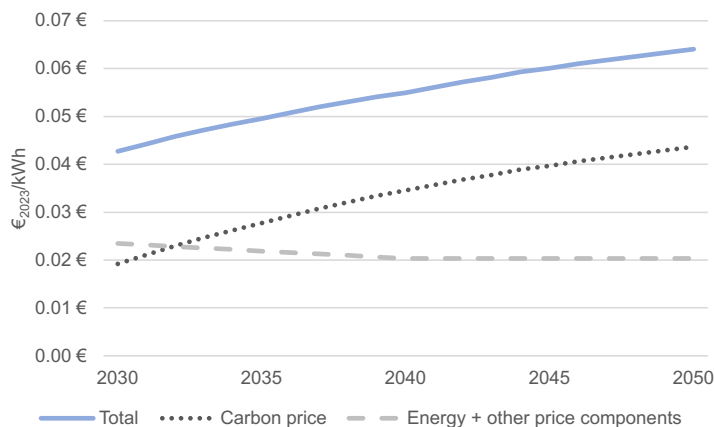


Figure 7. Assumed development of natural gas price and its components in Austria

To illustrate the influence of the assumed CO₂ pricing as a component of the total natural gas price and on the respective price developments in Figure 6 and Figure 7, the projection of the CO₂ price used equally for Germany and Austria between 2030 and 2050 is shown in Figure 8. The assumptions made here for future CO₂ price developments are based on the German Federal Environment Agency's Greenhouse Gas Projections 2024 for Germany and are equally applied to Austria and Germany due to the assumed EU-wide emissions trading scheme (EU ETS 2) after 2027 (Mendelevitch et al., 2024). The monetary values stated in the projection report were rebased to the year 2023 (€/2023/t CO₂). To calculate the CO₂ price per kWh, an emission factor of 55.8 t CO₂/TJ or 0.201 kg CO₂/kWh, respectively, is used as a standard factor provided by the German Federal Environment Agency (UBA), which is equally used in Austria (Bundesministerium Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (BMK), 2023; Juhrich, 2022). In accordance with the ETS Directive and the Monitoring and Reporting Regulation, carbon prices are based on direct emissions. For the alternative technologies and fuel, indirect emissions were equally excluded in the preliminary assessment.

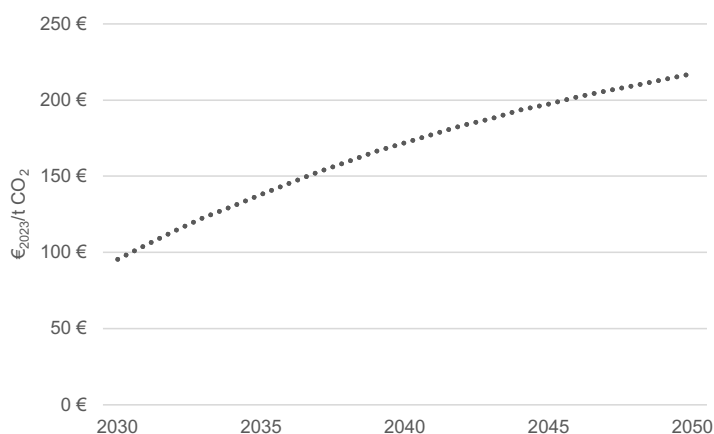


Figure 8. Assumed development of carbon pricing in Germany and Austria. *Source:* based on (Mendelevitch et al., 2024)

When interpreting economic results, it is important to recognise that forecasting future fuel and carbon prices is inherently uncertain. This is because these prices are influenced by the actions of various market participants and policymakers. The gas price projections in this preliminary impact assessment, for instance, are based on the assumptions outlined in the International Energy Agency's (IEA) World Energy Outlook 2024 report. However, observed gas prices in 2025 were significantly higher than the IEA's projections for 2030, and short-term prices may be affected by unpredictable external factors, such as geopolitical shocks or natural disasters.

This discrepancy highlights the challenges of long-term energy price forecasting, especially given the volatility of global energy markets and the influence of geopolitical and economic factors. Recent political developments have also introduced uncertainty into the timing of the implementation of the European Union's emissions trading system for buildings and road transport (ETS 2). Originally scheduled to be fully operational in 2027, there are provisions to delay implementation if energy prices are deemed to be exceptionally high. The assumptions of falling wholesale gas prices and a gradual increase in carbon prices - driven by the expansion of emissions trading - can therefore be considered conservative from today's perspective. If wholesale gas prices remain high, or if carbon prices rise faster than expected (e.g. due to slower decarbonisation progress in sectors covered by ETS 2), CBE4I technology would even gain a further economic advantage over conventional natural gas-fired systems. Conversely, if gas prices fall more sharply and/or carbon pricing fails to offset the cost advantage of fossil fuel systems, additional policy support through financial measures and schemes would be required to facilitate the market introduction of renewable energy solutions such as CBE4I technology.

RESULTS ACHIEVED SO FAR

Development of sales and stock

Sales depicted in Figure 9 represent total sales, which include the replacement of End-of-Life units that have been decommissioned. The stock data utilised for this preliminary impact assessment were derived from the sales and stock model developed by the Wuppertal Institute. A key assumption is that all technology alternatives possess identical stock levels, which consequently means that all sales are captured by one alternative exclusively, rather than being distributed among them. For new systems, stock calculations start from the reference year 2030, employing the equation given in the preceding section and factoring in the replacement of older systems in accordance with their described technical lifetime.

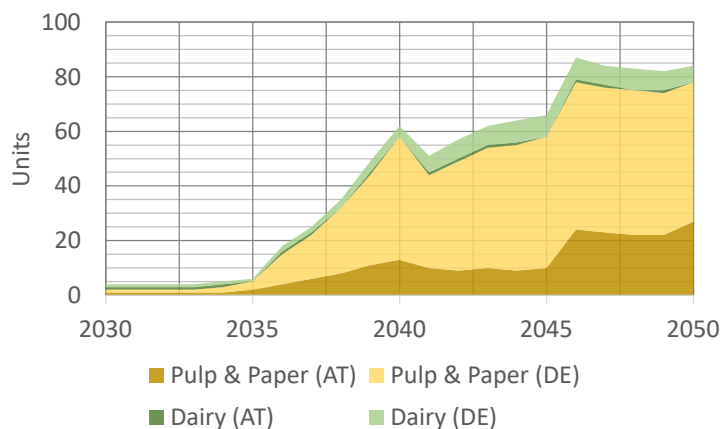


Figure 9. Development of sales for pulp and paper industry, without product gas extraction and dairy industry, without product gas extraction, in Austria and Germany until 2050

As a result of efficiency improvements and decarbonisation efforts, the EU Reference Scenario foresees a reduction in the total heat demand of the pulp and paper industry by 2050, and in particular a reduction in the share of fossil fuels (coal, oil and natural gas) (Kermeli & Crijns-Graus, 2020b). Declining sales figures over time reflect the aforementioned improvements in energy efficiency. Significant reductions in heat demand, driven by efficiency measures, cause a decline in sales between 2020 and 2025. This trend, although not shown in Figure 9, is incorporated as input data from project partner UU. Consequently, fewer End-of-Life units will require replacement after 2040.

The dairy industry exhibits considerably lower heat demand and, correspondingly, lower sales figures compared to the pulp and paper industry. This pattern holds true for both countries, but is particularly pronounced in Austria. Similar to the paper industry, the EU Reference Scenario projects a reduction in the dairy industry's total heat demand by 2050 due to efficiency gains. However, unlike some sectors, there isn't an equivalent sharp decline observed from one five-year period to the next in the dairy industry.

Figure 10 illustrates that cumulative sales result in a continuous increase in stocks. This increase becomes more pronounced after 2045, as the initial systems installed in the reference year reach the end of their technical lifespan and are replaced. By 2050, Austria's stock reaches 215 units for the pulp and paper industry and 15 units for the dairy industry. In Germany, the corresponding figures are 613 units for the pulp and paper industry and 93 units for the dairy industry.

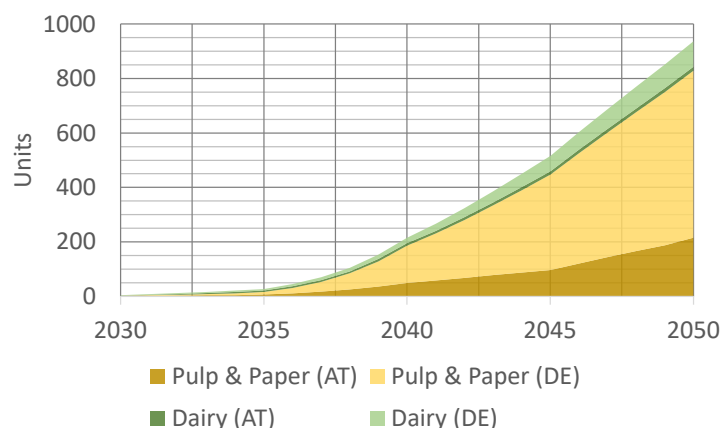


Figure 10. Total stock development for pulp and paper industry, without product gas extraction and dairy industry, without product gas extraction, in Austria and Germany until 2050

While the pulp and paper industry undoubtedly demonstrates higher sales and stock volumes in both countries, the substantial overall market potential of the European dairy industry and the associated opportunities for reducing emissions should not be overlooked.

Greenhouse gas emissions

As outlined previously, greenhouse gas emissions are derived from the multiplication of fuel consumption by the respective emission intensities. While for the calculation of the CO₂ price, only direct emissions were considered, the indirect emissions are also taken into account here. Based on the techno-economic analysis carried out by the project coordinator BIOS and other literature, GHG emission intensities of 8 kg CO₂/GJ (29 g CO₂/kWh) for wood chips and 71 kg CO₂/GJ (254 g CO₂/kWh) for natural gas are derived, irrespective of the country (Bundesministerium Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (BMK), 2023; Juhrich, 2022). Average Austrian GHG emissions of electric power generation are assumed to decrease from 40 kg CO₂/GJ_{el} in 2025 to 16 kg CO₂/GJ_{el} in 2050 and from 97 kg CO₂/GJ_{el} (2025) to 22 kg CO₂/GJ_{el} (2050) in Germany (E3Modelling, 2021).

For this preliminary impact assessment, it is assumed that both the CBE4I and the biomass boiler systems operate using wood chips, whereas the gas boiler uses natural gas. Biomass systems offer substantial greenhouse gas (GHG) emission savings, up to 90% compared to the gas boiler. The CBE4I system is particularly effective, outperforming the standard biomass boiler due to its higher efficiency, as illustrated in Figure 11. GHG emissions from grid electricity, arising from flue gas condensation using a heat pump, constitute a small fraction relative to fuel combustion emissions. This contribution further diminishes over time as the electricity mix integrates more renewables, evidenced by the widening gap between total GHG emissions and total stock (dashed line).

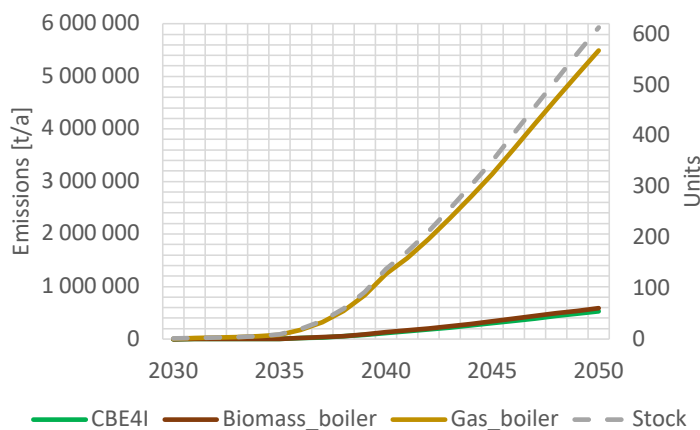


Figure 11. Total annual GHG emissions (solid lines) for CBE4I technology, biomass boiler with flue gas condensation and heat pump, and gas boiler and total stock volume (dashed line) of 5 MW units for pulp and paper industry in Germany

Air pollutant emissions

To calculate the absolute airborne emissions (i.e. CO, NO_x and TSP) for the stock, the fuel and grid electricity consumption of all units are multiplied by their corresponding emission intensities. National grid electricity emissions, specifically, are calculated using a synthesis of results from the PRIMES REF2020 scenario and EEA data. These emissions are projected to decrease over time due to the increasing integration of renewables into the electricity mix and the phasing out of conventional energy sources (E3Modelling, 2021; EMEP/EEA, 2019). A notable distinction exists in 2030: Austria's NO_x emissions are significantly lower than Germany's because more than half of Austria's electricity is generated from hydropower with minimal coal use,

while in Germany, the coal phase-out is timed for 2038 (Bundesministerium Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (BMK), n.d.; Federal Government, 2023).

Given that grid electricity is predominantly utilised by the heat pump, its associated emissions are a minor contributor compared to those from fuel combustion. The specific air pollutant emissions for each of the three technology alternatives are then calculated based on their individual fuel and electricity consumption, as shown in Figure 12 below.

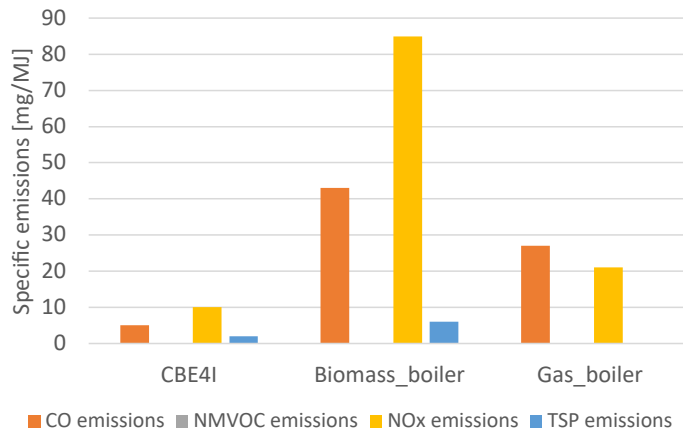


Figure 12. Specific emissions of the compared systems in relation to fuel input: CBE4I technology, biomass boiler with flue gas condensation and heat pump, and gas boiler. *Source:* Own illustration, based on data from the preliminary techno-economic analysis by project coordinator BIOS

The CBE4I technology produces very low emissions in all categories, although the natural gas-fired boiler is expected to have zero TSP emissions. The NMVOC emissions are so low that they are negligible according to the preliminary techno-economic analysis. Therefore, they were not taken into account in the preliminary impact assessment and were set to zero for all compared technologies. Compared to the conventional biomass plant, the emissions of the CBE4I plant are significantly lower. In particular, the new technology represents a major improvement and a clear step forward in the field of biomass combustion in terms of TSP emissions, but also CO and NO_x emissions are the lowest of the three systems considered.

The total NO_x emissions of the systems, calculated for the whole stock, are shown below. As can be seen in Figure 13, the CBE4I system has very low NO_x emissions, outperforming both other technologies, while the traditional biomass boiler systems have even higher emissions than conventional gas boilers.

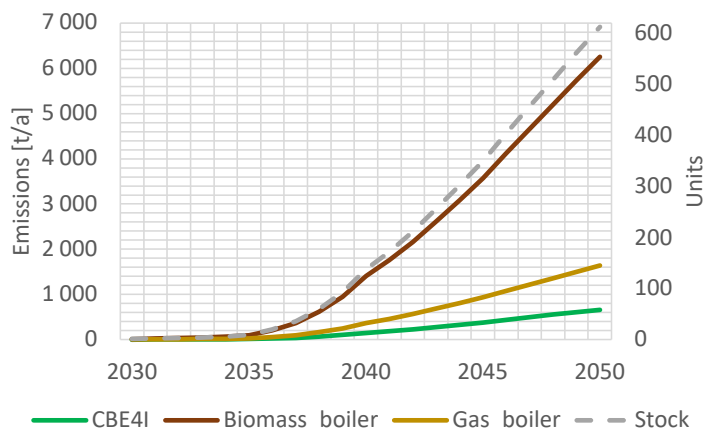


Figure 13. Total annual NO_x emissions (solid lines) for CBE4I technology, biomass boiler with flue gas condensation and heat pump, and gas boiler and total stock volume (dashed line) of 5 MW units for pulp and paper industry in Germany

In the case of TSP (Figure 14), the gas boilers have the lowest emissions compared to the biomass alternatives, but the CBE4I system clearly outperforms the state-of-the-art biomass boilers with a 70% reduction in TSP emissions.

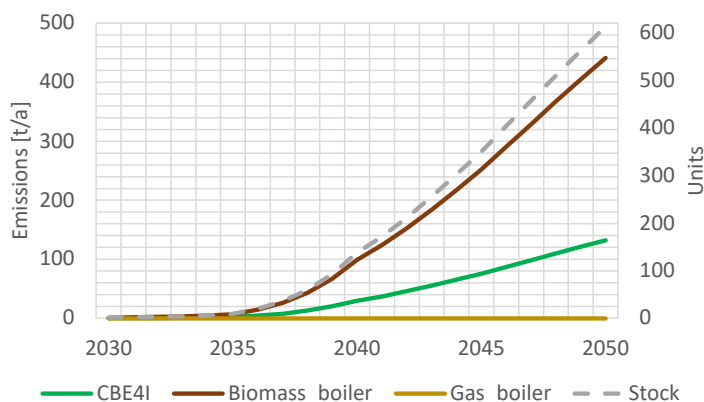


Figure 14. Total annual TSP emissions (solid lines) for CBE4I technology, biomass boiler with flue gas condensation and heat pump, and gas boiler and total stock volume (dashed line) of 5 MW units for pulp and paper industry in Germany

Total expenditures

The European Union's energy policy clearly emphasises the "energy efficiency first" principle, as enshrined in the Energy Efficiency Directive (EU/2023/1791), which makes the efficient conversion and use of energy one of the main objectives (European Commission, 2023a). The different total annual efficiencies of the technology alternatives analysed in the preliminary impact assessment are shown in Table 1.

Table 1. Total annual efficiency for the different technologies, related to NCV of fuel input

	CBE4I	Biomass_boiler	Gas_boiler
Thermal efficiency boiler + ECO	94%	92%	98%
Thermal efficiency condenser	17%	9%	—
Total thermal efficiency	111%	101%	98%

Source: CBE4I techno-economic analysis by project coordinator BIOS

As a determining factor in fuel and grid electricity consumption, high annual overall efficiency is essential. The high efficiency of the condensing unit in the CBE4I system gives a clear advantage in overall efficiency compared to the alternative technologies. The significance of these percentage differences in terms of total annual operating costs (of which about two thirds are fuel costs for biomass systems and almost all fuel costs for gas boilers) can be observed in Figure 15 as the stock numbers increase over time.

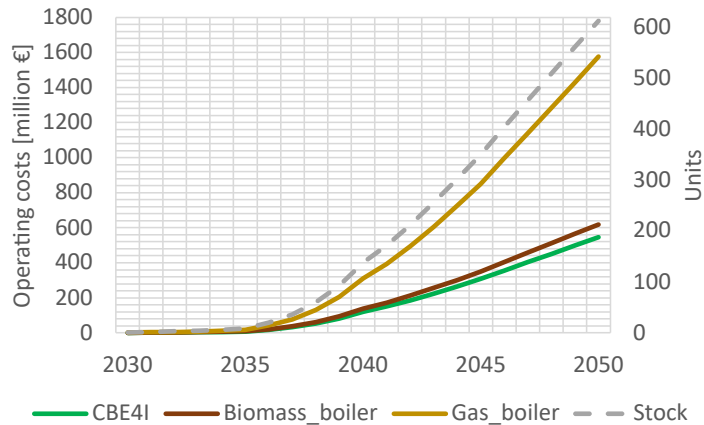


Figure 15. Total annual operating costs (solid lines) for CBE4I technology, biomass boiler with flue gas condensation and heat pump, and gas boiler and total stock volume (dashed line) of 5 MW units for pulp and paper industry in Germany

While all systems produce the same heat output, the CBE4I units consume a total of only about 18 400 GWh of wood chips in 2050, while the state-of-the-art biomass boilers consume more than 20 400 GWh of wood chips and the gas boilers even more than 21 600 GWh of natural gas. In terms of grid electricity consumption, gas-fired boilers consume the least, only 116 GWh in 2050, as no heat is recovered from the flue gas using a heat pump. Due to heat recovery by means of a heat pump, the CBE4I systems consume the most electricity in 2050 at around 1 200 GWh, more than ten times as much as the gas boilers. The biomass boilers consume about 1 000 GWh of electricity in 2050. However, due to their high overall efficiency, the total energy consumption as the sum of fuel and grid electricity consumption is the lowest for a stock consisting only of CBE4I systems, at about 19 600 GWh in 2050, which corresponds to 54% of the projected heat demand of the German pulp and paper industry at that time (Kermeli & Crijns-Graus, 2020b). In comparison, the biomass boiler systems consume 9.6% more energy (about 21 500 GWh) and the gas boilers 11% more (over 21 700 GWh).

While the running costs of the biomass systems are significantly lower than those of the fossil-fuelled gas boilers, the initial investment and installation costs are significantly higher than those of the gas boilers. In order to compare and illustrate the composition of costs for each technology alternative over time, Figure 16 normalises the total annual costs of the three systems to the cost of the CBE4I system, defining 100% in each year. This visualisation clearly shows the cost categories in relation to each other, unlike a comparison in absolute terms based on the entire stock. To emphasise the importance of a rising CO₂ price, it is shown separately as a yellow hatched bar rather than being included in the operating costs.

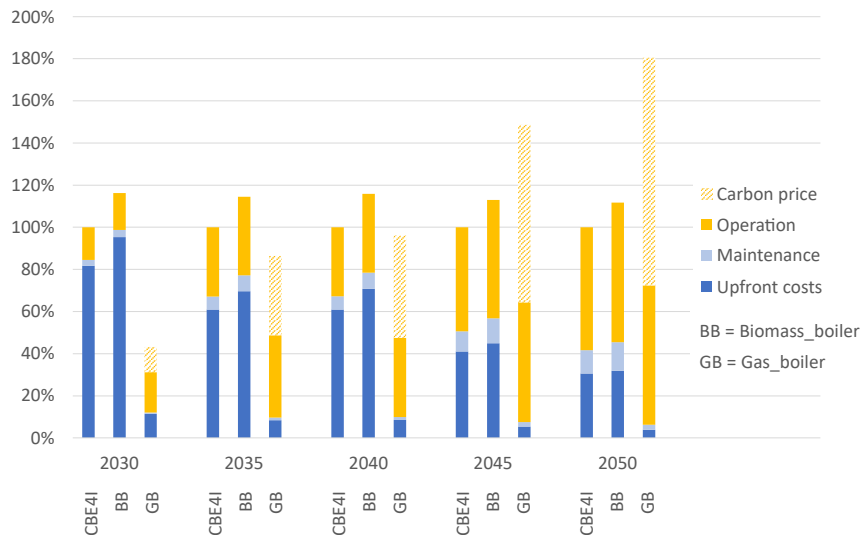


Figure 16. Composition of total annual costs for CBE4I technology, biomass boiler with flue gas condensation and heat pump, and gas boiler, normalised to the cost of the CBE4I system (= 100%) in the respective year

At the time of the planned market introduction in 2030, the CBE4I system is still expected to be more than twice as expensive as conventional gas boilers due to relatively high investment and installation costs. The high-efficiency CBE4I system is already more economical than the state-of-the-art biomass boiler system with even higher initial costs. It can be seen that the relative share of operating costs is higher for the fossil fuel system compared to the biomass alternatives, although the assumed CO₂ price is still very moderate and therefore not yet prominent. By 2035, the assumed CO₂ price has increased significantly and so has its contribution to the total annual cost of the gas boilers. Overall, gas boilers are still the cheapest technology option due to their very low initial cost, but the gap between the alternatives is narrowing. In 2040, the CBE4I system is almost competitive with gas boilers, for which the CO₂ price then accounts for about half of the cost. The CO₂ price remains the driving force behind the increase in the total cost of the fossil fuel system, which becomes particularly visible in 2045 and 2050. Conventional biomass boilers remain the most expensive technology option until 2040, but move into second place from 2045 onwards.

CONCLUSIONS AND OUTLOOK

Following the initial phase of the project, technical system design and preliminary techno-economic analysis provided crucial economic and system performance data, including emission factors for TSP, CO, and NO_x, as well as efficiency metrics. This preliminary impact assessment utilised these initial technical, energy efficiency, economic, and environmental parameters to analyse key indicators. By comparing these with data from state-of-the-art systems, the assessment quantifies and evaluates the potential improvements offered by the new technology. The overall impact assessment was conducted by the Wuppertal Institute, drawing upon preliminary results from the project coordinator BIOS and project partner Utrecht University, as well as data contributions from other project partners.

For this preliminary analysis, the Wuppertal Institute employed an internally developed stock model, which is to be further refined as the project progresses. The findings aim to inform decision-making regarding the overarching direction of technology development within the CBE4I project. Once final measurement and analysis data from the technology development phase become available, this preliminary impact assessment will be updated and refined. The final impact assessment, to be issued at the project's conclusion, will present the final results, compare various scenarios, and offer recommendations for the technology's long-term evolution.

Additionally, it will provide insights into how the EU policy framework could evolve to facilitate the market introduction of biomass-based industrial heat supply systems.

This paper presents part of these preliminary impact assessment results, integrating insights from the techno-economic analysis and a market study. The market study specifically assesses the new technology's potential within two illustrative industrial sectors. The EU Reference Scenario, serving as a baseline, projects a roughly 30% reduction in heat demand by 2050 (relative to 2015 levels) for both the pulp and paper and dairy industries, attributable to overall efficiency gains. Against this backdrop, an ambitious sales scenario was selected to model the installed base's evolution. Under this scenario, the innovative CBE4I technology is projected to constitute nearly 60% of the installed system stock by 2050. Based on these assumptions, the analysis indicates that transitioning from natural gas boilers to biomass-based systems can significantly reduce greenhouse gas (GHG) emissions, with reductions reaching up to 90% when utilising the new technology. However, replacing natural gas boilers with conventional biomass boilers, even those equipped with flue gas condensation, would lead to considerably higher emissions of TSP, NO_x, and CO. The new CBE4I technology offers a distinct advantage here, as it produces near-zero emissions. While conventional systems can, in principle, provide the required heat supply, the significantly enhanced efficiency of the new CBE4I technology helps to offset its higher initial investment costs compared to fossil fuel alternatives, in addition to delivering substantially reduced emissions.

When interpreting the economic results, it is crucial to acknowledge the inherent uncertainty in forecasting future fuel and carbon prices, as these are influenced by a multitude of market participants and geopolitical factors. The scenario-based analyses presented suggest that, under current CO₂ price projections, biomass-based heating systems are anticipated to achieve economic competitiveness with fossil gas boilers by 2040. At this point, the CO₂ price is expected to account for approximately half of the latter's total annual costs. Exempt from this, biomass-based systems generally have significantly lower running costs but higher upfront investment and installation costs. Specifically, the new CBE4I system requires over 2100 GWh less energy input relative to the total stock in 2050 compared to fossil gas boilers, a factor increasingly relevant to supply security concerns.

To accelerate the shift to renewable energy sources, transitional financial support in the form of investment grants should be considered to bridge the initial cost differential between renewable energy systems and fossil gas alternatives. The high efficiency and relatively low emissions of the new CBE4I technology would further amplify its economic advantage over conventional natural gas-fired systems in scenarios involving high wholesale gas prices or increasing carbon prices. Given the uncertainties in future CO₂ and gas price trajectories, it is prudent to design flexible policy mechanisms capable of adapting to market developments and ensuring sustained support for renewable energy deployment.

Another benefit of the new CBE4I system, which could not be explored in this preliminary assessment, is its capacity to utilise low-value biomass residues as fuel, rather than the wood chips assumed in this analysis. These residues are broadly available and do not compete with other biomass applications or agriculture for use. Although the infrastructure for collecting and transporting these materials is well-established in Germany and Austria, it remains a barrier to broader adoption in southern Europe, where further development is required. The CBE4I project is addressing this challenge as part of its further development work.

Finally, the comprehensive recovery of energy and materials through flue gas condensation and ash treatment - two key components of the CBE4I concept - ensures the CO₂ and mineral cycles are closed. This paves the way for the sustainable future use of biomass.

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LOGO SPACE

