REFORM

# Clean industrial heat: Electrification scenarios for selected sectors

ANNEX

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# Annex 1 – Electrification technologies

## Heat pumps

Heat pumps are unique among electrified heating technologies. Rather than directly converting electricity into heat, a heat pump uses electricity to transfer heat from an area of lower temperature (the "heat source") to an area of higher temperature (the "heat sink"). The heat pump consists of low low-temperature heat exchanger (evaporator), compressor, high-temperature heat exchanger (condenser), expansion valve and a closed loop of piping filled with a refrigerant. Refrigerant enters the evaporator as a low-temperature liquid, absorbs heat from the heat source at a low pressure, evaporates and leaves as a low-temperature vapour. Then pressure and temperature of the refrigerant are increased in the compressor to match the desired condensing temperature in the condenser, where refrigerant enters as a high-temperature vapour. In condenser refrigerant rejects heat to the heat sink by condensation at high pressure and leaves as a high-temperature liquid. The refrigerant, before returning to the evaporator, is directed to the expansion valve where its pressure and temperature drop.

A simplified technical process diagram for a compression heat pump can be found in figure below.

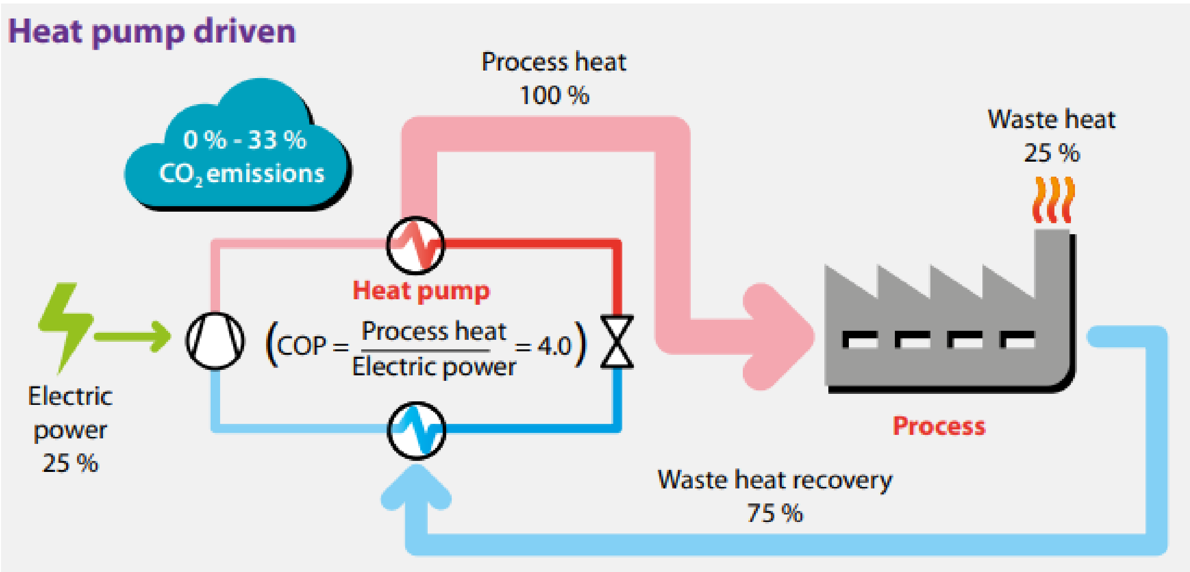


*Figure 1 Heat pump simplified process scheme, De Boer et al. (2020)*[1]

Heat pump efficiency is expressed as a coefficient of performance (COP), which is the ratio of heat transferred to the heat sink to the electricity consumed by the compressor. COP is

[1] de Boer, R., Marina, A., Zühlsdorf, B., Arpagaus, C., Bantle, M., Wilk, V., Elmegaard, B., Corberán, J., & Benson, J. (2020). *Strengthening Industrial Heat Pump Innovation: Decarbonizing Industrial Heat*. https://hthp-symposium.org/high-temperature-heat-pumps/white-paper-strengthening-industrial-heat-pump-innovation/

determined by the temperatures of the heat source and heat sink. Heat pumps are most efficient when delivering relatively small temperature increases, and their efficiency decreases as the temperature lift rises. The COP values range between about 1,6 and 5,8 with a temperature lift of 130°C to 25°C, respectively (Arpagaus, Bless, Schiffmann i Bertsch, 2018). For a given process temperature (i.e. the required temperature of the heat sink) the COP value can be raised by increasing the temperature of the heat source – e.g. by using more attractive waste heat streams (Hamid i inni, 2023).

Commercialised industrial heat pumps available in 2018 could provide heat sink temperature levels from 90°C to 165°C for a thermal power range between 20kW and 20MW, though heat pumps supplying 165°C of heat have relatively small capacities (660 kW). (Arpagaus, Bless, Schiffmann i Bertsch, 2018). Since then, technical progress has been made, particularly with higher capacity and higher temperature heat pumps. Higher temperature levels of the heat sink can be achieved by using heat sources with higher temperatures (e.g. waste heat from an industrial process) or by employing subsequent mechanical vapour recompression (MVR) or direct temperature boosting with an electric boiler. Research and development on heat pumps capable of reaching heat sink temperature of 200°C continues (Unterluggauer i inni, 2023), (Marina, Spoelstra, Zondag i Wemmers, 2021).

While industrial heat pumps are the most efficient electrification technology in terms of energy use (Madeddu i inni, 2020), they face significant challenges. Due to the necessity of an external heat source, the installation of the heat pump is more complex in technical aspects than electric boilers and requires specific site conditions (such as available waste heat source). The temperature lift of the heat pump is limited to <100°C between the inlet source and outlet sink. Although theoretically possible, higher temperature lifts are excluded since the COP will be too low to achieve any economic benefits (Marina, Spoelstra, Zondag i Wemmers, 2021). Moreover, heat pumps have high investment costs compared to electric boilers and gas boilers (Hamid i inni, 2023) and without carbon tax, the high-temperature heat pump can only compete economically against natural gas when electricity rates are low (Dumont, Wang, Wenzke, Blok i Heijungs, 2023). If carbon emissions are priced the same regardless of the emission source, high-efficiency heat pumps can compete with electricity on price and carbon footprint, even if the electricity is generated from natural gas. Higher investment costs and higher efficiency than electric boilers makes them more suitable as a baseload heat supply.

The paper industry and food and beverage industry have the biggest potential for integration of industrial heat pumps due to their high demand for heat up to 200°C (Obrist, Kannan, McKenna, Schmidt i Kober, 2023).

*Table 1 Technological processes within temperature range up to 200°C*

| Process | Temperature | Application |
|---|---|---|
| Drying | 200°C | Paper industry |
| Bleaching | 150°C | |
| Pulping | 100°C | |
| evaporation | 170°C | Food industry |
| roasting, pasteurization | 150°C | |

| | | |
|---|---|---|
| boiling | 120°C | |
| stabilization | 100°C | |
| fermenting | 40°C | |
| separation | 40°C | |

Possible heat sources for industrial heat pumps include waste heat form internal production processes, as well as external heat sources (geothermal heat, solar heat, waste heat from other industries, power plants, waste incineration plants).

Another medium temperature processes, such as distillation, could also integrate heat pumps to reduce fossil fuel consumption by utilising vapor recompression and bottom flashing heat pump-assisted systems ( Zhang i inni, 2020).

## Mechanical vapour recompression

Mechanical vapour recompression (MVR) finds application in distillation and evaporation systems, where it improves the overall energy efficiency of the industrial process. MVR uses a mechanical fan to recompress low pressure vapour to a slightly higher pressure and temperature. In distillation systems, MRV can directly compress top distillate vapour for use in the reboiler or can indirectly recovery heat from the distillate vapour (Walmsley, Atkins, Walmsley i Neale, 2016). Mechanical vapour recompression usually uses water, that takes part in the process itself, eliminating the need for a separate refrigerant circuit and heat exchangers. That allows for greatly reduced costs and increased efficiency. COP of mechanical vapour recompression is usually in the range between 3 and 10 (Madeddu i inni, 2020)

Mechanical vapour recompression is established, among others,:

- in food and beverages industry in milk evaporation systems (Walmsley, Atkins, Walmsley i Neale, 2016);
- in paper industry in evaporation of black liquor[2] in chemical pulp production (Liu i inni, 2023), (Variny, 2023);

The possibility of employing MVR was also analysed for the production of lactic acid, which is used in food and chemical industries (Cha i inni, 2022). Mechanical vapour recompression is a heat pumping technology, that can be classified as a kind of heat pump.

## Electric boilers

Electric boilers provide a viable alternative to fossil-fired boilers due to their versatility, ease of installation and potential for high-temperature applications. There are two types of electric boilers: resistance boilers and electrode boilers.

Electric boilers are commercially available for large-scale applications up to 70MW and can produce both steam and liquid heating media (Patel, Matalon i Oluleye, 2024). An electric boiler

[2] dark, liquid residual material from wood chips cooking, containing inorganic cooking chemicals and dissolved organics

can provide heat temperature levels up to 600°C and pressure levels up to 20 bar, which are not attainable by heat pumps. Compared to heat pumps electric boilers have lower efficiency (between 95% and 99,9%) and thus have higher operational costs, but due to higher achievable temperatures and lower investment costs they are easier to integrate into existing industrial systems. However, the potential for utilising electric boilers is not fully exhausted, because the higher electricity prices, relative to natural gas, act as a deterrent to direct electrification of industrial processes. Therefore, the adoption of electric boilers is highly dependent on effective policies (e.g. carbon tax) narrowing the price gap between natural gas and electricity.

**Resistance heating**

Electric resistance thermal equipment deploys an electric current to provide heating by material's electrical resistivity. There are two types of electric resistance heating:

- Indirect – The current runs through an electrical resistor, which heats up surrounding materials through convection, conduction, or radiation. This is the primary form of electric resistance heating currently applied in industry.
- Direct – The current runs through the material to be heated via its own electrical resistivity.

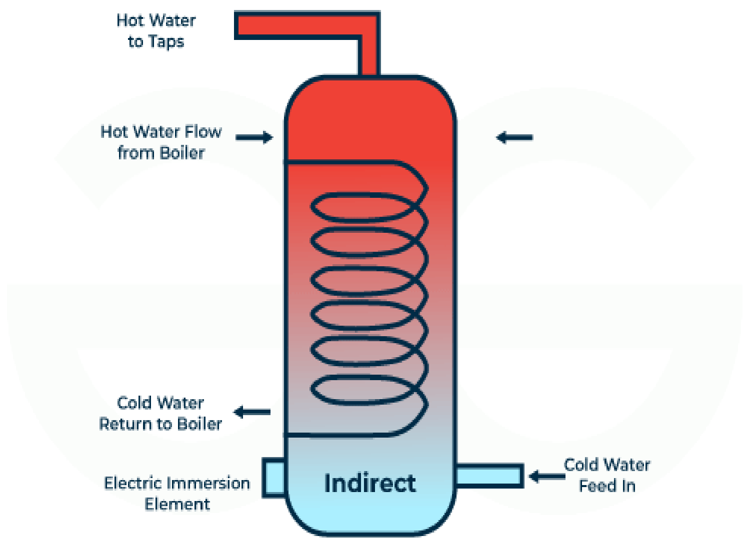


*Figure 2 Indirect resistance heating [3]*

Resistance heating is advantageous due to its ease of use and nearly 100% efficiency. Additional benefits involve increased controllability, reduced maintenance requirements, and the lack of combustion-related pollutants. Resistance heating is employed in a variety of industries, including food, printing, textiles, chemicals, glass, and plastics, for both low- and high-temperature applications.

Electric resistance heating constitutes one of the simplest and oldest form of electric heating. It can meet almost all industrial heating temperature requirements aside from highest temperature applications (e.g., cement kiln, steelmaking, metal fabrication). The idea is dependent on resistive element configuration and use of convective drivers (i.e., fans). Electric resistive heating elements are usually in indirect contact with the heated medium (e.g., water, process fluids, air). Nevertheless, it eliminates potential contamination of heated materials with fuel particulates or combustion flue gases.

[3] https://www.geeksforgeeks.org/what-is-resistance-heating/

Many centrally located gas-fired steam systems could be replaced by electric resistance boilers. Electric boilers are nearly 100% efficient, come in any capacity up to 100 MW, and can produce hot water or steam up to 220˚C. Their response time is quite quick, and several European manufacturers have already implemented flexible operations for electric boilers to capitalize on the low-cost intermittent power supply derived from renewable sources.

For instance, calcinating and other high-volume, high-temperature processes could be powered by electric resistance. An electric version of Calix's flash calciner, which processes minerals like clay and limestone by heating them to approximately 1000˚C, is being developed by an Australian business.

Indirect resistance heating may be applied in different configurations:

- Electric furnaces: use high-temperature heating elements, usually made of SiC, $MoSi_2$, nickel-chromium alloy that can reach temperatures in the range of 1000-2000°C
- Electric ovens: the ohmic heating elements mounted in the oven heat the products through convection and radiation. Forced circulation of the air may be required for uniform and more rapid heating
- Electric boilers: are available in a wide range from kW’s to MW’s. Unlike their combustion-based counterparts, electric boilers do not produce any harmful gases and hence can be installed near the point of use.
- Circulation heaters: are compact heating devices for liquids and gases. They have ohmic heating elements immersed in the fluid stream.

**Electrode boilers**

Electrode boilers operate by passing an electric current between submerged electrodes, which directly heats the water through electrical conduction. Electric boilers exhibit high energy efficiency, with approximately 99% of the consumed energy being converted into heat. When powered by renewable electricity sources, these boilers do not produce greenhouse gas emissions (GHG).

The installation and maintenance of electrode boilers are simpler and more cost-effective compared to fuel-burning boilers due to the reduced need for additional equipment. Notably, electrode boilers do not require combustion exhaust systems and occupy significantly less space than conventional boilers. Moreover, boilers operate with significantly less noise, an important factor in applications where boilers are located near occupied spaces.

Electrode boilers are characterized by high operating flexibility, low investment costs, and high efficiency. These boilers achieve powers ranging from 3 up to 60 $MW_t$ with efficiency >99%. The principle of the operation of such boilers is the use of electricity from renewable energy sources, whereby these systems are zero-emission solutions.

Electrode heat boilers use electrodes immersed in an insulated tank filled with water to generate heat. These boilers can operate as steam wheels, preparing steam for technological purposes, or as water boilers.  Water in an electrical circuit acts as a resistance, where electrical energy is converted into heat, causing the water to heat up. After heating, the water is transferred to the heat exchanger, where it transfers heat to the water network. An additional tank inside the boiler contains feed water - the source of the refrigerant for the tank with electrodes. The circulation pump, located behind the heat exchanger, ensures water circulation in the system. Currently, it is possible to supply an electrode boiler as a device generating high-pressure steam. For instance, PARAT company has developed a design for a boiler operating at a design pressure of up to 85 bar and with a power of up to 30 MW, operating in the voltage range from 6 to 24 kV. It is the first modern high-pressure steam boiler of this type in the world. Its use instead of traditional boilers fired with fossil fuels will significantly reduce the level of emissions of harmful substances. In addition, the PARAT electrode boiler can be delivered as a hybrid device combining the function of generating hot water and steam in one system, which has been patent pending. Thanks to the ability to automatically switch between heating modes, this boiler is extremely flexible and can meet the diverse heating needs of any installation, both in terms of hot water and steam demand. There are low (LV) and high (HV) voltage electrode boilers available on the market. Low-voltage boilers are powered by electricity at 230, 400 or 690 V, and standard models offer a nominal thermal power in the range of 300-5000 kW. HV boilers, on the other hand, are dedicated to systems with higher power, reaching 3-60 MW. A power supply is possible at a voltage of 6-24 kV, which often allows direct connection of the boiler to the network without the need to use a transformer, which contributes to lower investment costs per unit[4].

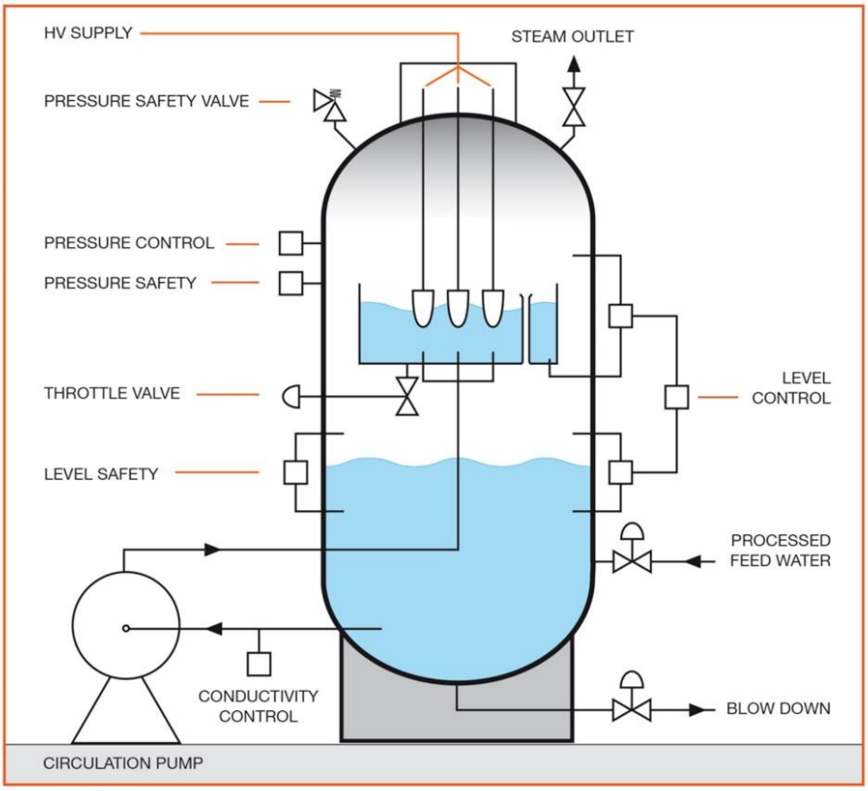


*Figure 3 Diagram of the water electrode boiler[5]*

[4] https://www.parat.no/products/industry/parat-ieh-high-voltage-electrode-boiler/

Electrode heat boilers are used in conditions where free or surplus electricity is available. Currently, a popular and competitive solution for high voltage (HV) boilers is their integration with heat accumulators. This connection allows frequency regulation in the power grid and the absorption of excess energy from wind or solar power plants. In the case of a low share of renewable sources, as is the case in the Polish power system, an alternative source of cheap electricity is the purchase of energy during periods of low demand, especially at night.

The most important features of this energy technology include:

- An electrode boiler can be used for decarbonization only when it is powered by cheap electricity from a renewable energy power plant or gas cogeneration.
- Economical use of the boiler requires a heat accumulator.
- Quick start-up allows the boiler to be used as a peak-reserve source in the absence of access to the gas network.
- Flexibility of the boiler allows for the provision of regulatory services in the power grid (frequency regulation, network balancing)[5].

## Infrared and microwave heaters

Infrared heaters are used in food industry for drying and heating. Infrared heaters can be combined with convective, conductive and microwave heating (Riadh, Ahmad, Marhaban i Soh, 2014). Energy efficiency of infrared heaters ranges between 60% and 90% (Madeddu i inni, 2020).

In infrared heating heat is transferred by radiation, the wavelength of which is determined by the temperature of the emitting body—the higher the temperature, the shorter the wavelength. In infrared heaters air in contact with the equipment is not heated, thus infrared drying is more energy efficient than convective air drying. (PAWAR i PRATAPE, 2015). Moreover, infrared heaters have other advantages over the conventional drying methods such as short process time, increased uniform product temperature, better-quality finished products, high degree of process control parameters, high heat transfer coefficient and space saving (Rastogi, 2012). However, infrared radiation does not penetrate deeply into materials, heating only the surface, so in some cases infrared drying has to be combined with other drying methods (e.g. microwave).

Microwave energy is delivered directly to the material through molecular interaction with the electromagnetic field. Microwave heaters generate heat throughout the volume of the material resulting in volumetric heating (Sun, Wang i Yue, 2016). Microwave heating is used, among others, in food processing and drying processes – sometimes in combination with infrared heating. (Ekezie, Sun, Han i Cheng, 2016). The energy efficiency of microwave heaters ranges between 50% and 85% (Madeddu i inni, 2020).

Infrared and microwave heaters, just as electric boilers use only energy from the electric grid, as opposed to heat pumping technologies. Therefore their electricity consumption and thus

[5] Technology Data for Energy Plants for Electricity and District heating generation, August 2016, updated 2017-18, Danish Energy Agency

operating costs are high. The use of infrared or microwave heaters therefore is usually dictated by process requirements and not by economy of their use. There is almost no possibility to use those two technologies flexibly, other than shifting work schedules or using electricity storage.

## Summary

The most efficient electrification technology available is heat pumps, but the higher the temperature, the less advantage they have (excluding applications where waste heat of similar temperature is available). For medium-temperature processes, electric boilers are a versatile source that can replace fossil-fuel boilers.

*Table 2 Electrification technologies for low- and medium-temperature industrial heat*

| Technology | Technological maturity | Applications | Efficiency/COP | Capacity | Maximum temperature |
|---|---|---|---|---|---|
| Compression heat pumps | Established in industry (for low-temperature heat) | Space heating; hot water; low-pressure steam; drying | COP 1,6-5,8 | Up to 20 MW | >180°C (limited by availability of high-temperature heat source, practicality and capital costs) |
| Mechanical vapour recompression (MVR) | Established in industry | Energy recovery (e.g. in distillation, evaporation) to provide steam and heat | COP 3-10 | Up to 1MWe (electricity consumption) | <100°C |
| Electric boilers | Established in industry | Space heating; hot water; thermal oil; steam generation | 95%-99,9% | 70-100 MW | 600-1000°C |
| Infrared heaters | Established in industry | Drying; food processing | 60%-90% | Depends on applications | 1370°C; 100°C (food processing) |
| Microwave heaters | Established in industry | Drying; food processing | 50%-85% | Depends on applications | 2200°C; 100°C (food processing) |

# Annex 2 – Simulation model of electrification

This publication includes a simplified economic model of investment in various heat sources for the industry, to cover distinct heating needs in 2050 perspective. The aim was to show, what is the difference in cost, energy consumption and CO2 emissions between three scenarios.

## Three scenarios

The scenarios were deliberately designed to be very distant to each other, to show costs and benefits of each strategy. No scenario, especially not "business-as-usual", should be treated as the one that is particularly probable or recommended. It is most likely that the actual future heating mix of the industry will be something between all three. Additionally, there is much uncertainty around the future output of the industry, which can be affected by structural changes in the economy and by "black swan" events.

### Business-as-usual

"Business-as-usual" scenario prolongs current annual energy consumption and energy mix into 2050. Direct combustion of fossil fuels continues at a present pace, however electricity and heat bought from electric grid and heating grid become progressively more decarbonised. The purpose of this scenario is to show a reference, where no decarbonisation of industry takes place other than scope 2 emissions reduction.

### Mixed scenario

This scenario involves a complete phase-out of solid and liquid fossil fuels by 2040 and a complete gas phase-out by 2050. Some decarbonisation is done using solid biomass, but more with direct electrification with either heat pumps or electric boilers. For food and beverage and for chemical industry some solid biomass is replaced with electricity as well. For paper industry no biomass substitution with electricity is taken into account because this sector has high volume of combustible by-products. Paper industry is already optimised to utilise lower-quality wood and is situated where the access to this resource is optimal. Therefore if there will be any excess woody biomass that could be used for energy needs, paper industry will be the first consumer in line to use it. Current use of electric heating and heat imports were not subjected to change.

The purpose of mixed scenario is to show a path, where solid biomass is treated as one of the many acceptable decarbonisation solutions and where businesses can increase its use where technical or economical considerations make this an optimal choice.

### Full electrification scenario

This scenario involves a full transition to electricity by 2050. Solid and liquid fossil fuels are phased out by 2040, while biomass and natural gas are phased out by 2050. All heat use, with the exception of current heat imports, are converted to electrified heating with either heat pumps or electric boilers.

The purpose of full electrification scenario is to show the costs and effects of a policy aimed at full conversion of all heating demand to electricity.

## Assumptions about prices and technology

Costs and technical parameters of various heating technologies have been taken from either official documents, such as Polish NECP or from other respectable sources. Where there is conflicting data or wide uncertainty for the future developments, in-house assumptions were proposed.

### Capital and financial expenditures

For each heating technology, a price tag for its construction or deep modernisation was added. It is based on our inner assumptions, consulted with experts.

Coal-fired heat sources are not likely to be built anymore, but will require extensive repairs and new flue-gas cleaning installation to survive. For other fossil-based heaters less modernisation will be required to keep them running, but they usually have a lifetime of 25 years or less, so in their case amortisation/cost of replacement has been included. Construction or deep modernisation price tag for each technology is presented below:

*Table 3 Capital expenditures for construction or deep modernisation of heating sources*

| Technology | Detail | Price (EUR/kWth) |
|---|---|---|
| Fossil fuel boiler | Coal (deep modernisation) | 190 |
| | Natural gas | 100 |
| | Any other fossil-derived (LPG, fuel oil, refinery gas, etc.) | 190 |
| Biomass or waste boiler | - | 580 |
| Existing heat import connection | Distributed steam | 100 |
| Heat pump | Temperature 0-100 C | 500 |
| | Temperature 100-150 C | 700 |
| | Temperature 150-200 C | 870 |
| | Temperature 200-500 C | 1300 |
| Other electric heating | Any electric heating technology, that is not a heat pump and thus based on pure conversion of electric energy into heat (i.e. electric boilers, infrared and microwave heaters) | 175 |

Investment such as these is usually financed by the industrial companies from borrowed money. Various financing option exists, some have higher borrowing costs, some have lower. In order to provide a technology-neutral approach, irrespective of predicted lifetime of different technologies, we have calculated CAPEX with its associated financial cost as a sum per megawatt-hour of heat, that adds to LCOH. Financial cost has been calculated using a discount rate of 7% and payback time of 25 years, with payments of equal height throughout this period. At this discount rate and payback time, the sum of payments is roughly twice as high as would be upfront cost. No preferential loans from the EU have been added to the calculus. Average annual utilisation rate of 75% has been included to account for sectoral overcapacity and downtime.

## Energy and CO2 emission costs

Energy carrier price consists of two elements – wholesale price and distribution cost. Wholesale prices of coal, natural gas and CO2 allowances have been taken from Polish NECP (according to European Commission's guidance) and are included in the table below. Price of other fossil fuels, such as LPG and fuel oil have been assumed to be 90 EUR/MWhth for 2030 and 100 EUR/MWhth after this date.

*Table 4 Price assumptions for energy costs calculations*

| Price (EUR/Mwhth) | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|
| Coal | 11.9 | 11.9 | 12.6 | 13.3 | 14.4 |
| Natural gas | 42.8 | 42.8 | 42.8 | 44.3 | 45.4 |
| Any other fossil-derived (LPG, fuel oil, refinery gas, etc.) | 90.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| Biomass or waste | 18.9 | 19.2 | 19.3 | 19.5 | 19.7 |
| Distributed steam | 24.5 | 24.6 | 24.9 | 25.7 | 26.5 |
| Electricity | 117.3 | 110.5 | 92.4 | 90.0 | 83.2 |
| CO2 allowance (EUR/t CO2) | 132 | 155 | 179 | 194 | 210 |

Electricity cost for 2030-50 has been taken from tables of hourly electricity price for four weeks representative of four seasons supplied by ARE (Agencja Rynku Energii – polish Energy Market Agency). For electricity price calculation, a baseload price has been taken, since many industries have stable electricity consumption profile or have to work on weekdays on daytime shifts. Price of distributed heat has been calculated as the average of coal price, natural gas price and biomass price, since these three energy carriers are about to play the main role in the heating mix in the near future.

Distribution cost of energy carriers consists of grid fees for electricity and natural gas and transport costs for all other energy carriers. Grid fees have been assumed to stand at 50 EUR/MWh for electricity and 10 EUR/MWh for natural gas. Transport costs have been assumed to be 20% for solid fuels such as coal and wood and 10% for liquid fuels, since the latter have higher energy density and higher price per unit of energy. Cost of heat distribution has been calculated as 20% of the financial value of this energy carrier, which should represent the cost of transport and energy losses.

*Table 5 Transport/distribution cost and on-site emissivity of final energy carriers*

| Energy carrier | Distribution cost | Emissivity on-site (tCO2/MWhth) |
|---|---|---|
| Coal | 20% of fuel value | 0.337 |

| | | |
|---|---|---|
| Natural gas | 10 EUR/MWhth | 0.200 |
| Any other fossil-derived (LPG, fuel oil, refinery gas, etc.) | 10% of fuel value | 0.250 |
| Biomass or waste | 20% of fuel value | 0 |
| Distributed steam | 20% of energy value | 0* |
| Electricity | 50 EUR/MWh | 0* |

** Emissions from bought energy carriers (such as electricity and heat) are included in Scope 2 emissions*

CO2 emission cost has been calculated using emission factors per unit of energy. Those are listed in the table above. Emissions from scope 2 have been calculated separately and not included in the financial analysis, since they are already included in the energy price. CO2 prices have been shown in the Table 4.

Electricity mix in the national grid has been assumed to follow the WAM scenario from the latest NCEP. NCEP shows electricity production and CO2 emissions from electricity and heat production until 2040, which allows (with rough approximation) for calculating emissivity of electricity in the grid. Emissivity of distributed heat has been assumed to be 40% of electricity emissivity. This should factor in progressing decarbonisation of the heat sector. While heat sector is likely to decarbonise slower than the electricity sector, the use of biomass and highly efficient gas-fired cogeneration should lower the emissivity in the short term. Emissivity values used in calculations are shown in table below:

*Table 6 Emissivity of final energy carriers from Scope 2 (kg CO2/MWh)*

| Emissivity (kg CO2/MWh) | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|
| Electricity | 685 | 374 | 201 | 57 | 23 | 0 |
| Heat | 274 | 149 | 81 | 23 | 9 | 0 |

Secondary emissions (emissions from extraction and transport of energy carriers, as well as non-CO2 greenhouse gas emissions) have not been counted.

## Efficiency of energy use

For each heating technology, efficiency or SCOP has been calculated. SCOP for heat pumps has been calculated as 60% of ideal Carnot efficiency between heat source and heat sink. Heat sink temperature is the maximal temperature in the scope under consideration, while heat source temperature is an approximation between cases when waste heat at decent temperature is available and cases when it is not. For high temperature heat pumps, heat source temperature is elevated, because they will be used only when waste heat is available, otherwise low efficiency and high capital cost would exclude their use. This is shown in the “Applicability” value in the table below.

*Table 6 Heat pumps efficiency and applicability*

| Temperature range | Average heat source temperature | Average heat sink temperature | Calculated SCOP | Applicability | Applicability limited primarily by: |
|---|---|---|---|---|---|
| 0-100°C | 27°C | 100°C | 3.07 | 90% | Intermittency or process requirements |
| 100-150°C | 27°C | 150°C | 2.06 | 80% | Intermittency or process requirements |
| 150-200°C | 60°C | 200°C | 2.03 | 60% | Waste heat availability and temperature |
| 200-500°C | 100°C | 260°C | 2.00 | 20% | Required temperature, waste heat availability and temperature |
| 500+°C | n/a | n/a | n/a | 0% | Out of heat pumps practical range |

Efficiency of other heating technologies has been shown in the table below:

*Table 7 Thermal efficiency of selected heating technologies*

| Technology | Detail | Efficiency (%) |
|---|---|---|
| Fossil fuel boiler | Coal (deep modernisation) | 89% |
| | Natural gas | 93% |
| | Any other fossil-derived (LPG, fuel oil, refinery gas, etc.) | 90% |
| Biomass or waste boiler | - | 84% |
| Existing heat import connection | Distributed steam | 99% |
| Other electric heating | Any electric heating technology, that is not a heat pump and thus based on pure conversion of electric energy into heat (i.e. electric boilers, infrared and microwave heaters) | 99% |

## Other operational expenditures

Costs such as repairs, staffing, electricity consumption (for combustion-based technologies), fuel additives and flue gas cleaning (for solid fuels combustion) and other operating costs have been provided in the table below.

*Table 8 Operational expenditures other than energy and emission costs*

| Technology | Detail | Price (EUR/MWhth) |
|---|---|---|
| Fossil fuel boiler | Coal (deep modernisation) | 14.5 |
| | Natural gas | 2.0 |
| | Any other fossil-derived (LPG, fuel oil, refinery gas, etc.) | 2.0 |
| Biomass or waste boiler | - | 14.5 |
| Existing heat import connection | Distributed steam | 2.0 |
| Heat pump | Temperature 0-100 C | 2.3 |
| | Temperature 100-150 C | 2.3 |
| | Temperature 150-200 C | 3.0 |
| | Temperature 200-500 C | 4.0 |
| Other electric heating | Any electric heating technology, that is not a heat pump and thus based on pure conversion of electric energy into heat (i.e. electric boilers, infrared and microwave heaters) | 3.5 |

## Calculated heat price

For each heating generating technology, a calculation of lifecycle cost of MWh of heat for each 5-year period has been calculated. This consists of short-run marginal cost, which in theory allows for fuel switching in case of dynamic pricing, and discounted capital cost per technology, which must be paid regardless of use. The two are presented below:

### Operating costs

Useful energy has been converted to final energy using efficiency or SCOP of heat generating technologies. Final energy has been priced according to its price in a given year, including transport/distribution cost. Then on-site CO2 emission cost and maintenance cost have been added. The sum of the total is presented in the table below:

*Table 9 Short-run heat price for various heating sources*

| | Price (EUR/MWhth) | | | | |
|---|---|---|---|---|---|
| Technology | 2030 | 2035 | 2040 | 2045 | 2050 |
| Coal boiler | 75.0 | 82.7 | 91.7 | 97.7 | 104.6 |
| Natural gas boiler | 85.1 | 89.7 | 94.5 | 99.1 | 103.5 |
| Other fossil-fueled (LPG, fuel oil, refinery gas, etc.) boiler | 145.0 | 163.0 | 169.0 | 172.7 | 176.7 |
| Biomass or waste boiler | 41.6 | 41.9 | 42.1 | 42.4 | 42.6 |
| Distributed steam | 31.8 | 31.8 | 32.3 | 33.2 | 34.1 |
| Electric resistance heating | 126.9 | 120.1 | 101.9 | 99.6 | 92.9 |
| Heat pump 0-100 C | 42.2 | 40.0 | 34.1 | 33.4 | 31.2 |
| Heat pump 100-150 C | 61.5 | 58.2 | 49.5 | 48.4 | 45.2 |
| Heat pump 150-200 C | 63.3 | 59.9 | 51.0 | 49.9 | 46.6 |
| Heat pump 200-500 C | 65.1 | 61.7 | 52.7 | 51.6 | 48.3 |

## Discounted capital cost

Investment cost has been included in price of heat as annual payment of investment loan, divided by annual heat production measured by utilisation rate. Investment costs and discount rate have been calculated as fixed, therefore discounted capital cost does not change with time.

*Table 10 Discounted capital cost for various heating sources*

| | Price (EUR/MWhth) | | | | |
|---|---|---|---|---|---|
| Technology | 2030 | 2035 | 2040 | 2045 | 2050 |
| Coal boiler | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| Natural gas boiler | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Other fossil-fueled (LPG, fuel oil, refinery gas, etc.) boiler | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| Biomass or waste boiler | 7.1 | 7.1 | 7.1 | 7.1 | 7.1 |
| Distributed steam | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |

| | | | | | |
|---|---|---|---|---|---|
| Electric resistance heating | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 |
| Heat pump 0-100 C | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 |
| Heat pump 100-150 C | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 |
| Heat pump 150-200 C | 10.6 | 10.6 | 10.6 | 10.6 | 10.6 |
| Heat pump 200-500 C | 15.9 | 15.9 | 15.9 | 15.9 | 15.9 |

## LCOH

Lifecycle cost of heat includes both operating costs and discounted capital cost. A table of LCOH for a given year is presented in a table below:

*Table 11 LCOH for various heating sources*

| | Price (EUR/MWhth) | | | | |
|---|---|---|---|---|---|
| Technology | 2030 | 2035 | 2040 | 2045 | 2050 |
| Coal boiler | 77.3 | 85.0 | 94.1 | 100.0 | 106.9 |
| Natural gas boiler | 86.3 | 90.9 | 95.7 | 100.3 | 104.7 |
| Other fossil-fueled (LPG, fuel oil, refinery gas, etc.) boiler | 147.3 | 165.3 | 171.3 | 175.0 | 179.0 |
| Biomass or waste boiler | 48.6 | 48.9 | 49.2 | 49.5 | 49.7 |
| Distributed steam | 33.0 | 33.1 | 33.4 | 34.4 | 35.3 |
| Electric resistance heating | 129.1 | 122.2 | 104.0 | 101.7 | 95.0 |
| Heat pump 0-100 C | 48.3 | 46.1 | 40.2 | 39.5 | 37.3 |
| Heat pump 100-150 C | 70.1 | 66.8 | 58.1 | 57.0 | 53.8 |
| Heat pump 150-200 C | 73.9 | 70.5 | 61.6 | 60.5 | 57.3 |
| Heat pump 200-500 C | 81.0 | 77.6 | 68.6 | 67.5 | 64.1 |

## Scenarios for each industry

Pathways for each industry were introduced as a given and have not been optimised for cost or any other criteria. The main input to the simplified model in the form of a spreadsheet are values for conversion ratio from one technology to another. Based on this, the model calculates final energy use, emissions and costs.

## Current heating mix

The basis for calculation is the current energy consumption by the industry, as provided by Eurostat. The latest detailed data is provided for 2021, more general data for 2022 has been included, when possible in direct form, where the data has been insufficiently detailed, proportion between energy carriers was taken from data for 2021, while trend for year-on-year change has been taken from comparing more general data for 2022 with data for 2021. Such simplified calculation is done mostly for marginal energy carriers in the Polish industry, such as oil derivatives.

Eurostat data allows for quite detailed division of energy carriers per specific use. Some cathegories however remain bundled together or too poorly quantified. One such example is biogas and biomethane, which is classified together with natural gas. In our study we cannot differentiate between methane of fossil and biological origin for existing installations, for new biogas plants it is included in "biomass and waste" category.

*Table 12 Categorisation by Eurostat compared to the calculations in this report*

| **Eurostat classification** | **Our classification** |
|---|---|
| [Fossil] Solids | Coal |
| Natural gas and biogas | Natural gas [and existing biogas/biomethane] |
| Refinery gas | Other fossil fuels |
| LPG | |
| Diesel oil and liquid biofuels | |
| Fuel oil | |
| Other liquids | |
| Derived gases | |
| Biomass and waste | Biomass and waste |
| [New biogas/biomethane] | |
| Distributed steam | Distributed steam |
| Thermal cooling | |
| Direct heat/Process heat/Drying - Electric | Electricity – current (assumed electric resistance heating) |
| Direct heat/Process heat/Drying - Microwave | |
| Electric cooling | |
| Low-enthalpy heat: electricity | |
| [All kinds of non-heat electricity use, e.g. lighting, machinery] | Final energy – demand for electricity (outside of heating mix, calculated separately) |

Heat demand in each industry has been divided into 5 temperature ranges (the same temperature ranges as for heat pumps plus 500+°C range, which is out of heat pumps application). It has been assumed for the ease of calculation, that each energy carrier currently provides a mix of heat demand proportional to demand at each range.

## Conversions from one source of heat to another

All heat-related final energy consumption has been converted to useful energy to allow for calculating changes in the energy mix. Then percentage changes at consecutive time intervals have been proposed. The first change occurs between 2022 and 2030, then energy mix is recalculated every 5 years, toward 2050. "Business-as-usual" scenario involves no changes in the energy mix, other two scenarios aim for total decarbonisation with or without biomass use. Fossil fuels phase-out is not uniform, coal and liquid fuels are phased out until 2040, natural gas by 2050. In the interim, some rise in natural gas consumption can occur.

Conversions have been added into the model by forcing a given percentage of existing useful heat
In case of .demand to convert to specific different energy carriers by the next time period
part of the electrification is about to be done with heat pumps and part with electric ,electrification
the same share of heat at each ,For simplicity .(resistance heating (for example electrode boilers
A share of heat pumps versus electric .temperature level is about to be electrified in each time period
.(resistance heating is dictated by heat pumps applicability (decreasing with the necessary temperature
,Currently electrified heat will not be converted into any other energy carrier under any scenario
therefore its structure has not been investigated.

Conversions generate increases in heat demand for certain technologies and decreases for the others. Those translate later into investment costs. It is possible for some technologies to achieve increase and decrease at the same time, particularly for natural gas and biomass in the interim period of decarbonisation, where some coal-fired boilers switch to them as an immediate solution.

## Costs borne out by industry

Changing energy prices and changing energy mix (excluding BAU scenario) have effect on costs. For costs calculation, new energy mix is converted back to final energy carriers using values for efficiency and heat pumps SCOP.

Useful heat production by each technology is multiplied by LCOH to provide total costs estimates for each industry. This is used to compare the competitiveness of each scenario. Additionally, energy costs and investment costs are also calculated separately, to show the financing needs and the impact on the energy sector.

# Annex 3 Electrification in food and beverages industry

This annex discusses in detail calculations and results for food and beverages industry. It also includes tables and charts that were judged to be superfluous in the main part of the publication.

## Data sources

Food and beverages industry in Poland is very diverse. There are companies and facilities of different sizes. Production processes are very diverged. To get an approximation about energy consumption in the sector and the approximate use of this energy, we have used data for year 2021 from JRC-IDEES database (Rozsai et al., 2024) and extrapolated energy use trends for year 2022 based on Eurostat sectoral data. Division of heat needs into temperature ranges was based on a study of Compass Lexecon, with contribution of the enel Foundation and ERCST.

## Current heating mix

JRC-IDEES database divides energy use into many categories an then for some of them shows how this demand is fulfilled. For conciseness and clarity, we have merged together those ways of energy use, which can be treated together from the perspective of the energy mix. Various uses of electricity, such as lighting, pumps and compressors, as well as other electric-operated machinery, are classified together as non-heat demand for electricity, which is not about to change under any scenario.

Current electric-based heating has been also treated as one category. Technologies such as microwave heating, electric resistance-heated ovens and electricity-based cooling have been included in a category “current electricity-based heating”, which is not likely to evolve in the foreseeable future.

Heating with other heat sources than electricity will be subject to change. Therefore it has been divided across energy carriers, wherever possible. A table with historical energy consumption in the food and beverages sector (in original units – ktoe) is presented below:

*Table 1 Current final energy mix of the food and beverages industry*

| | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|
| Solids [Coal] | 569.97 | 527.91 | 502.10 | 501.77 |
| Refinery gas | 0.00 | 0.00 | 0.00 | 0.00 |
| LPG | 24.01 | 24.94 | 27.29 | 58.83 |
| Diesel oil and liquid biofuels | 28.52 | 21.82 | 20.49 | 44.18 |
| Fuel oil | 15.86 | 12.07 | 10.25 | 22.09 |
| Other liquids | 0.44 | 0.17 | 0.09 | 0.20 |
| Natural gas and biogas | 820.44 | 796.47 | 828.01 | 811.24 |

| | | | | |
|---|---|---|---|---|
| Derived gases | 0.00 | 0.00 | 0.00 | 0.00 |
| Biomass and waste | 18.64 | 15.53 | 9.82 | 37.91 |
| Ambient heat | 0.00 | 0.00 | 0.00 | 0.00 |
| Distributed steam | 96.77 | 92.97 | 83.26 | 76.86 |
| Electricity [current use] | 252.30 | 251.80 | 260.82 | 260.82 |

## Useful energy and share of each energy carrier

Final energy has been converted to useful energy by multiplying final energy consumption by efficiency of each heat generating technology, as provided in Annex 1. The result is shown in the graph below:

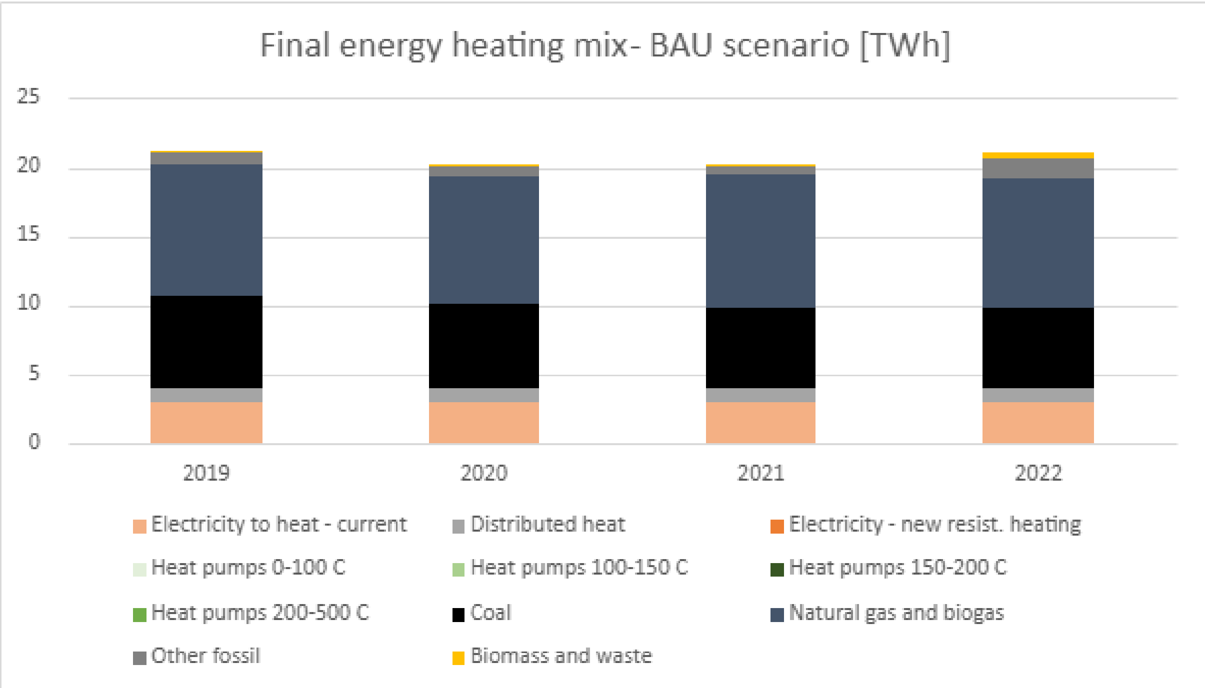


*Figure 1 Current useful energy consumption in food and beverages industry*

Older data (not included in this study) shows, that a steady decline in coal use witnessed in the data for years 2019-22 is a long-term trend since at least the start of the XXI century. A rise in "other fossil" in 2022 comes from a partial substitution of natural gas with LPG during the fossil fuels price crisis precipitated by aggressive policy of the Russian Federation. Food and beverages industry exhibits a slight decline in 2020 and 2021, which may be a result of the Covid-19 pandemic and recession. A percentage share of each energy carrier in the heating mix is shown below:

*Table 2 Current heating mix (useful energy) of the food and beverages industry*

| | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|
| Solids [Coal] | 31.2% | 30.3% | 28.8% | 27.7% |

| | | | | |
|---|---|---|---|---|
| Refinery gas | 0.0% | 0.0% | 0.0% | 0.0% |
| LPG | 1.3% | 1.4% | 1.6% | 3.2% |
| Diesel oil and liquid biofuels | 1.6% | 1.3% | 1.2% | 2.4% |
| Fuel oil | 0.9% | 0.7% | 0.6% | 1.2% |
| Other liquids | 0.0% | 0.0% | 0.0% | 0.0% |
| Natural gas and biogas | 44.9% | 45.7% | 47.5% | 44.7% |
| Derived gases | 0.0% | 0.0% | 0.0% | 0.0% |
| Biomass and waste | 1.0% | 0.9% | 0.6% | 2.1% |
| Ambient heat | 0.0% | 0.0% | 0.0% | 0.0% |
| Distributed steam | 5.3% | 5.3% | 4.8% | 4.2% |
| Electricity [current use] | 13.8% | 14.4% | 15.0% | 14.4% |

## Scenarios for the future of food and beverages industry

The future of the energy mix of the food and beverages sector has been calculated with two assumptions in mind: first is the need to withdraw from the use of solid and liquid fossil fuels as soon as possible – coal has to be withdrawn because of CO2 emissions and other pollution, while liquid fuels are most expensive and most vulnerable to external price shocks. For this reason, some of the demand is switched to natural gas and biomass in the short term. The second assumption is the smaller availability of sustainable biomass than for the paper industry. Food and beverages industry will have access to a limited amount of sustainable (including waste) biomass, so even in the "mixed" scenario this is not the preferred decarbonisation option. In the "electric" scenario biomass, including waste byproducts is redirected toward biomethane production outside of the sector.

### Business-as-usual scenario

In this scenario heat demand is fulfilled using the same energy carriers as now, right until 2050. The resulting final energy mix is shown in the graph below:

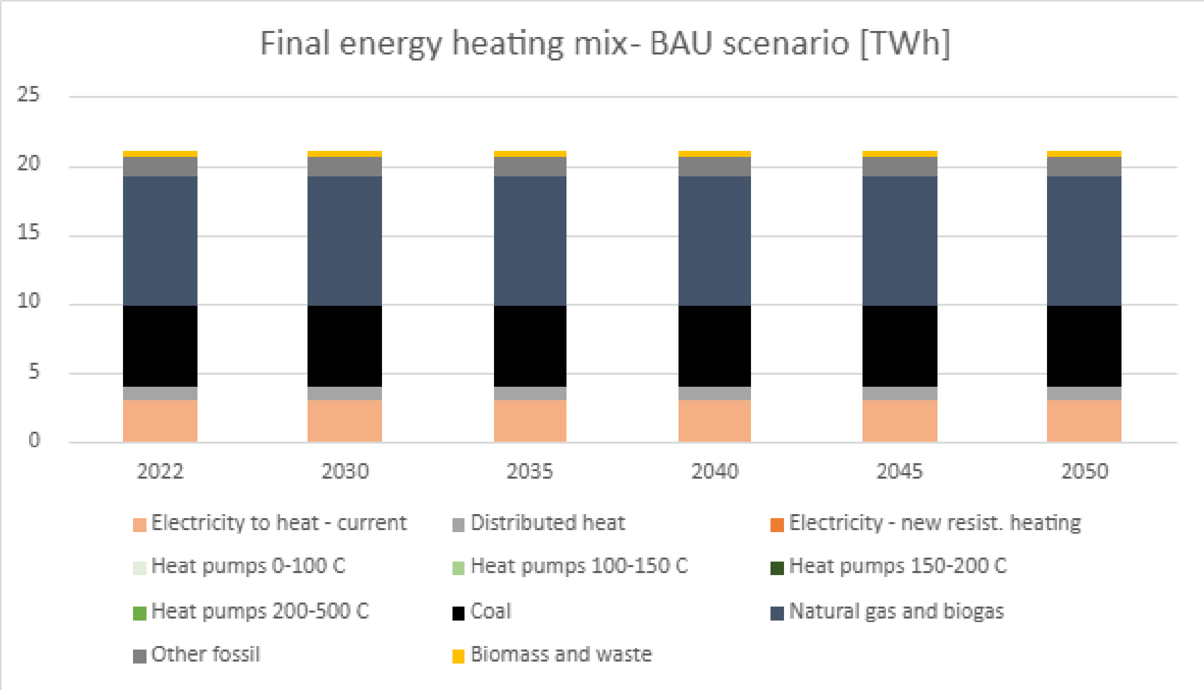


*Figure 2 Final energy mix in food and beverages industry in BAU Scenario*

Keeping the current energy mix results in continuing high CO2 emissions. Overall carbon intensity of the heat mix of the food and beverages industry would decrease due to the decarbonisation of electricity and district heat. This improvement will thus only come from decreased emissions in Scope 2.

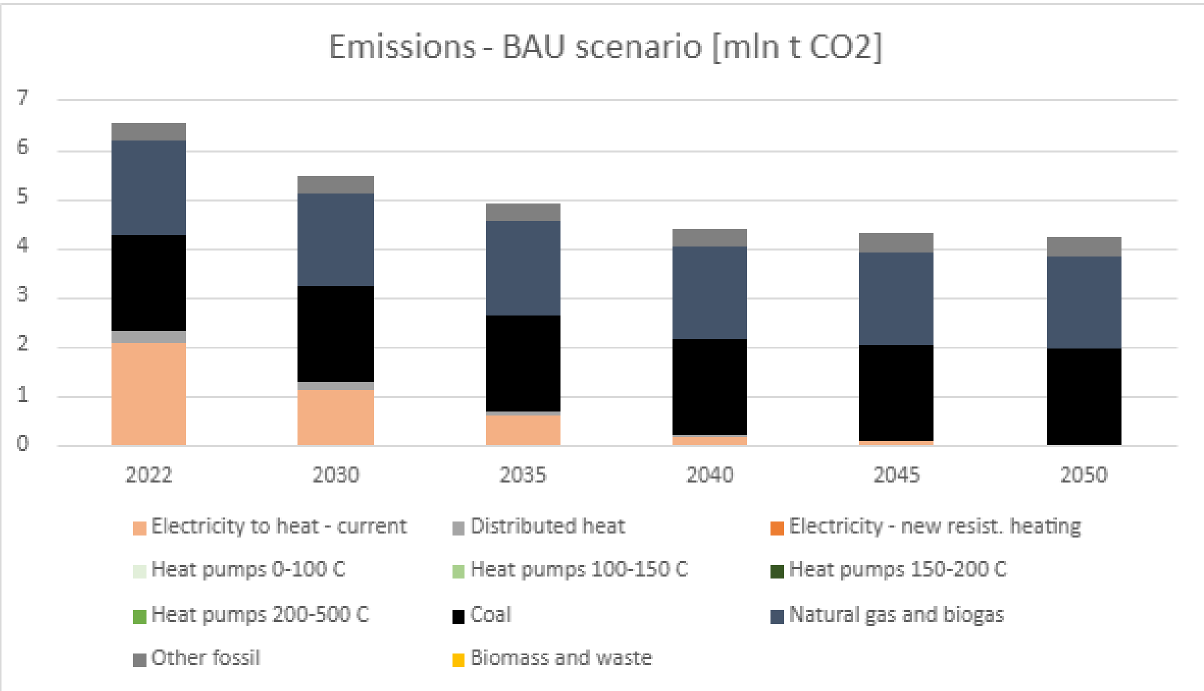


*Figure 3 CO2 emissions from Scope 1 and 2 in food and beverages industry in BAU Scenario*

In BAU scenario keeping the current energy mix leads to consistently rising CO2 emissions costs. This adds to the energy price, which is relatively low and to low investment and operational costs of fossil fuel boilers. The costs evolution across time is shown below:

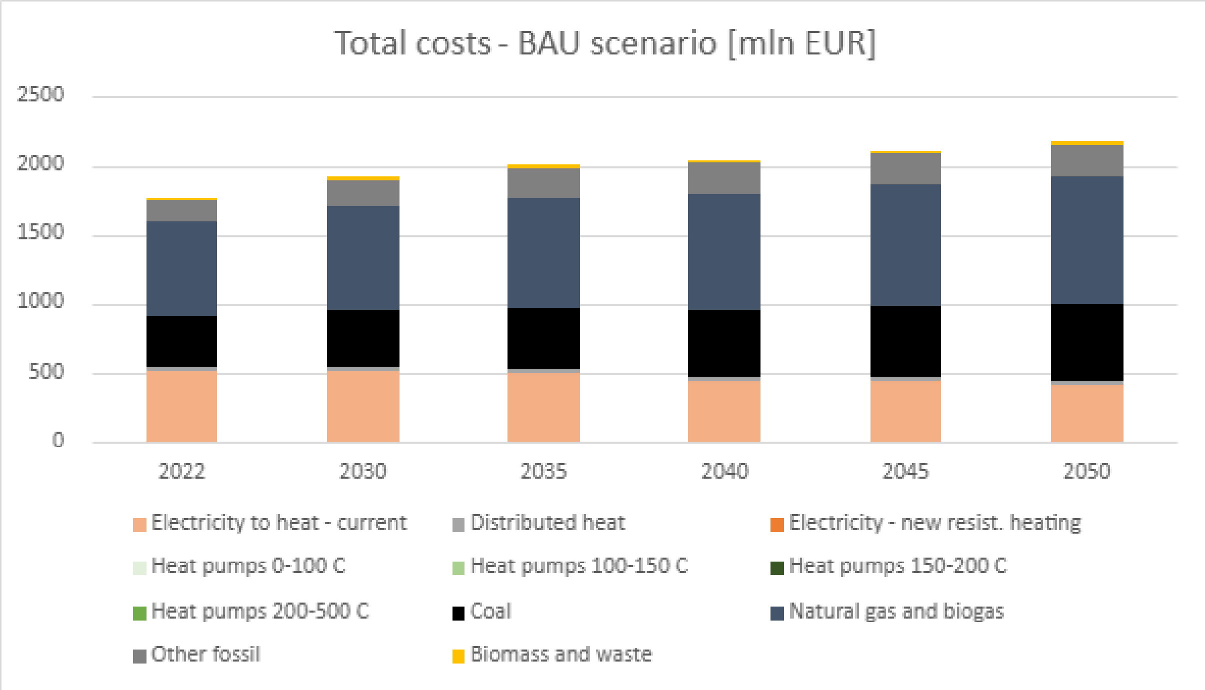


*Figure 4 Total costs of heat (LCOH) in food and beverages industry in BAU Scenario*

## Mixed scenario

In the mixed scenario heat demand is gradually decarbonised using electrification and biomass. Coal and liquid fossil fuels are replaced until 2040 with electricity, biomass and (until 2030) natural gas. Natural gas is replaced until 2050 with electricity and biomass. Some biomass is converted to electricity throughout the period. A table showing the rate of conversions in each period is shown below:

*Table 3 Share of useful energy got from each energy carrier converted into a different energy carrier before a given date in the food and beverages industry*

| Conversion ratio until | 2022 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|
| Coal-to-gas | - | 15% | - | - | - | - |
| Coal-to-biomass | - | 5% | 10% | 20% | - | - |
| Coal-to-electric | - | 20% | 40% | 80% | - | - |
| Liquid fuels-to-gas | - | 15% | - | - | - | - |
| Liquid fuels-to-biomass | - | 5% | 10% | 20% | - | - |
| Liquid fuels-to-electric | - | 20% | 40% | 80% | - | - |
| Gas-to-biomass | - | 5% | 5% | 10% | 10% | 20% |
| Gas-to-electric | - | 15% | 20% | 40% | 40% | 80% |
| Biomass-to-gas | - | - | - | - | - | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| Biomass-to-electric | - | 10% | 10% | 10% | 10% | 10% |

The resulting final energy mix is shown in the graph below:

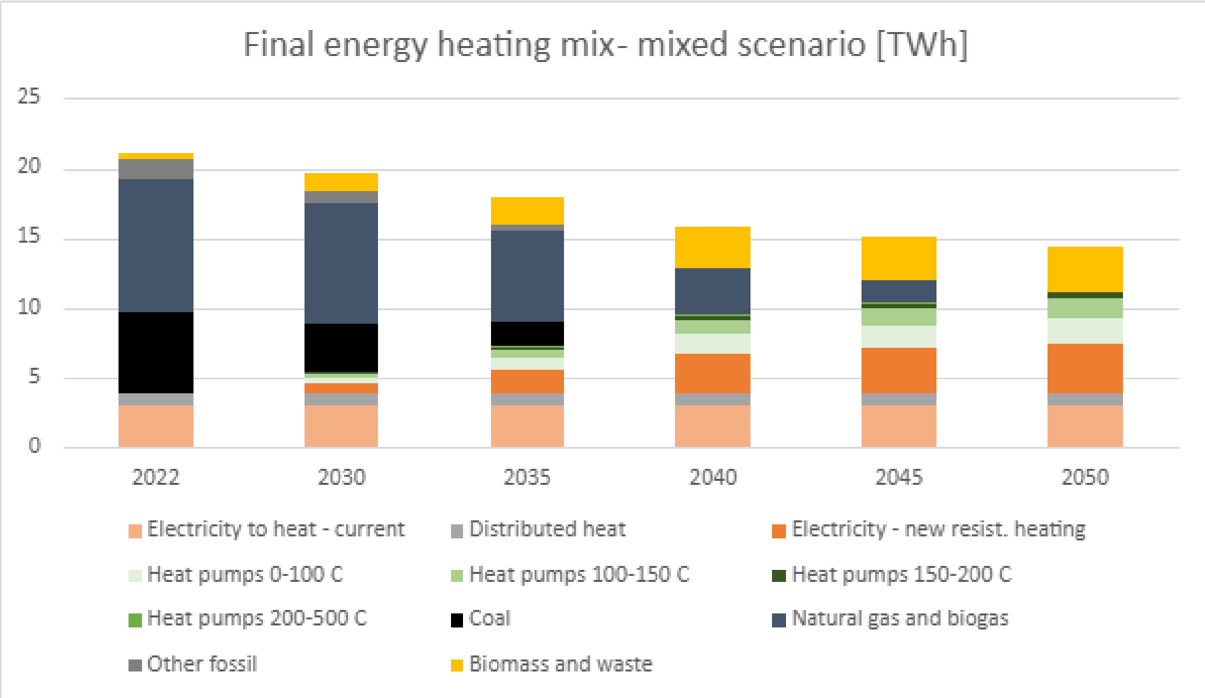


*Figure 5 Final energy mix in food and beverages industry in mixed scenario*

Conversion from fossil fuels to electricity and biomass leads to a gradual decrease in CO2 emissions. This stems both from reduced direct fossil fuels burning (Scope 1 emissions) and from the ongoing decarbonization of the imported energy (Scope 2 emissions). The results are shown below:

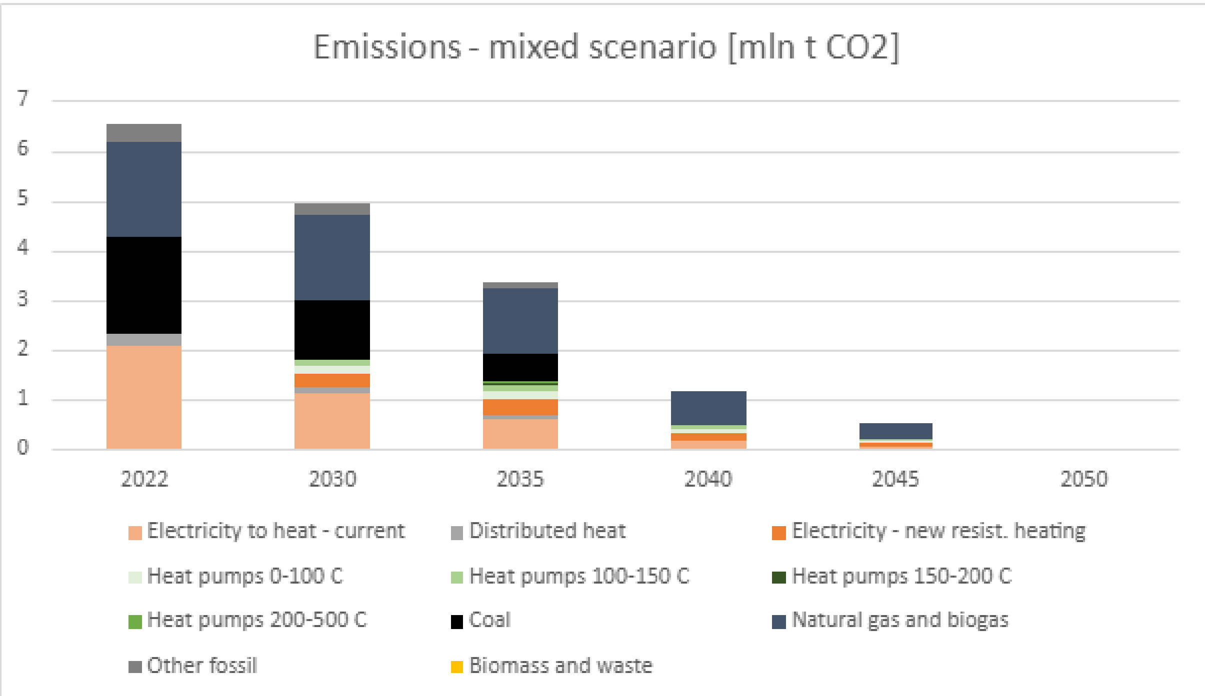

*Figure 6 CO2 emissions from Scope 1 and 2 in food and beverages industry in mixed scenario*

Mixed scenario leads to gradual reduction in CO2 emission costs (despite their increasing price), but the technologies that replace fossil fuels often have higher investment or operating costs. Nevertheless, decarbonization leads to decreasing overall energy costs, as shown below:

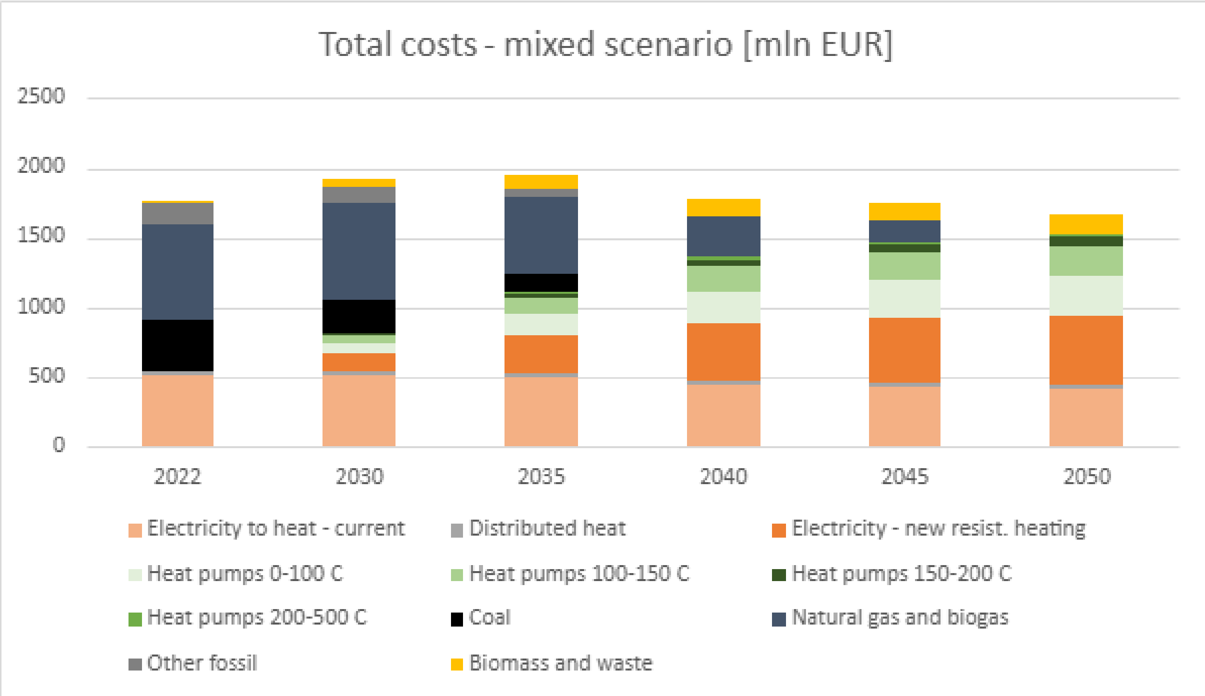


*Figure 7 Total costs of heat (LCOH) in food and beverages industry in mixed scenario*

## Electric scenario

Electric scenario shows the effects of full electrification of food and beverages industry by 2050. Coal and liquid fossil fuels are replaced until 2040 with electricity, biomass and natural gas. However, in contrary to the mixed scenario, conversions to biomass are reduced since 2030 and from the 2040 biomass is on a fast phase-out trajectory, together with natural gas. This leads to an electricity-only heating mix by 2050. A table showing the rate of conversions in each period is shown below:

*Table 4 Share of useful energy got from each energy carrier converted into a different energy carrier before a given date in the food and beverages industry*

| Conversion ratio until | 2022 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|
| Coal-to-gas | - | 15% | - | - | - | - |
| Coal-to-biomass | - | 5% | 5% | 5% | - | - |
| Coal-to-electric | - | 20% | 45% | 95% | - | - |
| Liquid fuels-to-gas | - | 15% | - | - | - | - |
| Liquid fuels-to-biomass | - | 5% | 5% | 5% | - | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| Liquid fuels-to-electric | - | 20% | 45% | 95% | - | - |
| Gas-to-biomass | - | 5% | 5% | - | - | - |
| Gas-to-electric | - | 15% | 20% | 50% | 50% | 100% |
| Biomass-to-gas | - | - | - | - | - | - |
| Biomass-to-electric | - | 10% | 10% | 20% | 50% | 100% |

The resulting final energy mix is shown in the graph below:

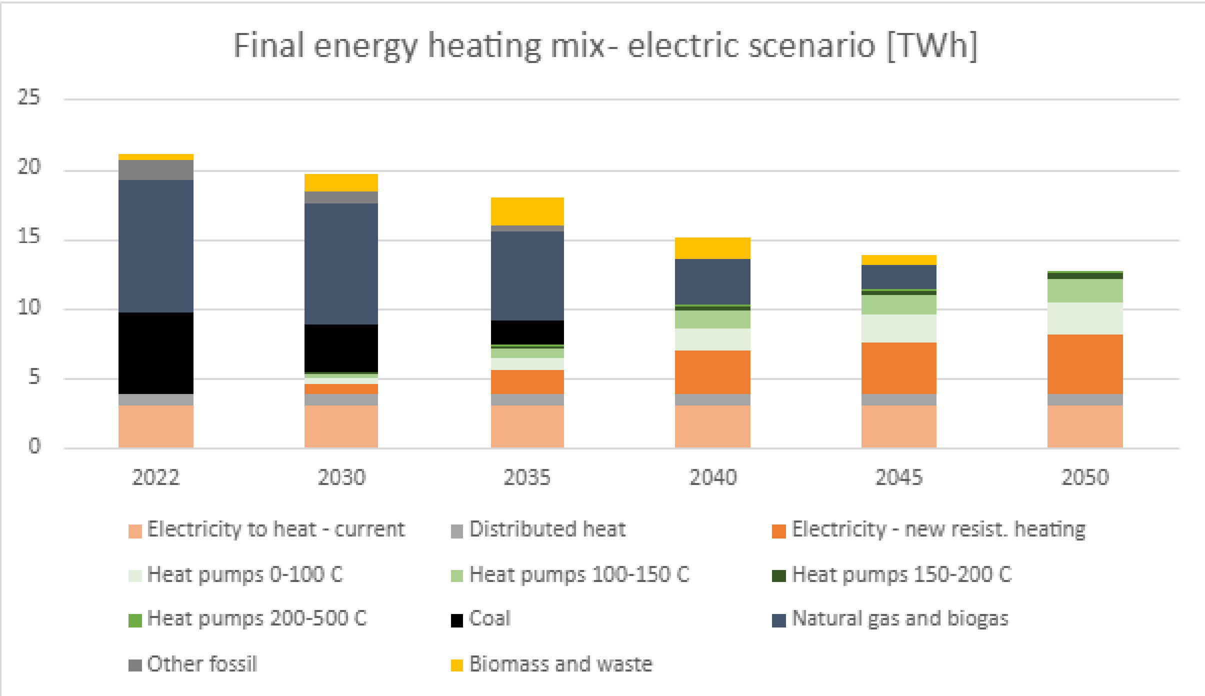


*Figure 8 Final energy mix in food and beverages industry in electric scenario*

Conversion from fossil fuels to electricity leads to gradual decrease in CO2 emissions. This stems both from reduced direct fossil fuels burning (Scope 1 emissions) and from the ongoing decarbonization of the imported energy (Scope 2 emissions). Since biomass is treated in this study as a zero-emission energy source, replacement of biomass with electricity does not lead to any additional CO2 emission reduction. Climate impact of the electric scenario is marginally higher than in the mixed scenario when CO2 from burning biomass is not taken into account:

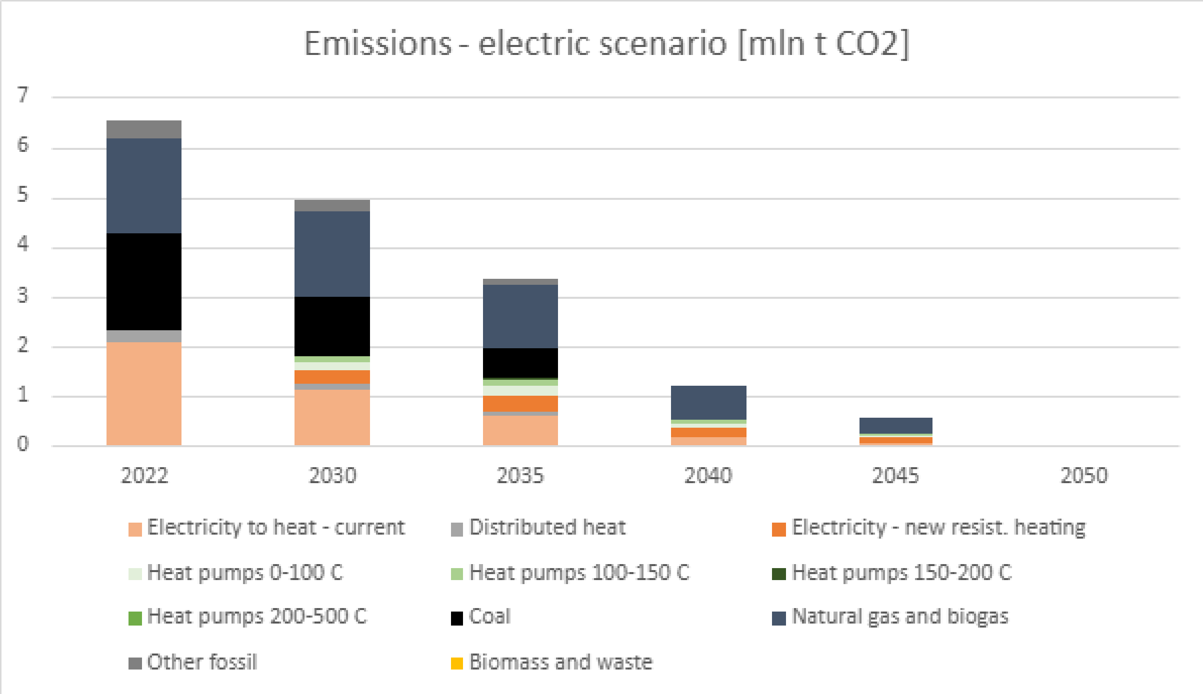


*Figure 9 CO2 emissions from Scope 1 and 2 in food and beverages industry in electric scenario*

Electric scenario leads finally to zero CO2 emission cost, however since electricity is more expensive than biomass, total costs of heat are slightly higher than in mixed scenario. The difference is very small owing to a small use of biomass in mixed scenario and very effective electrification due to high potential for heat pump use. The results are shown below:

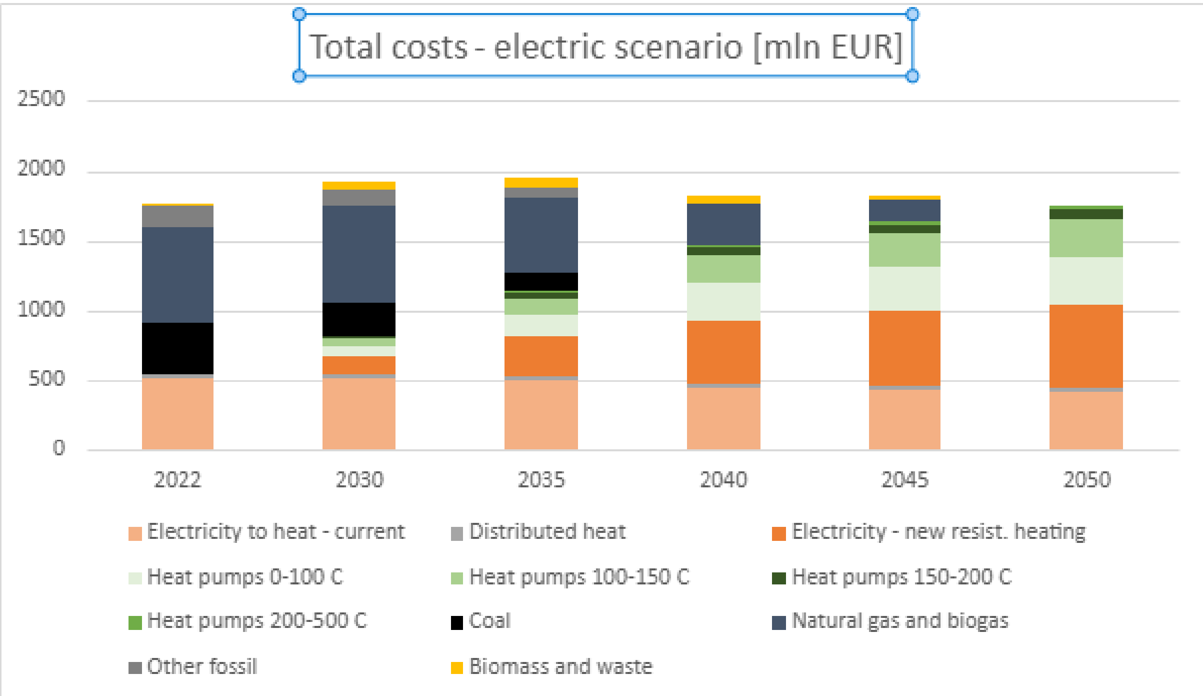


*Figure 10 Total costs of heat (LCOH) in food and beverages industry in electric scenario*

## Scenarios summary456789101112

Full electrification of the food, beverage and tobacco industry could increase the sector's electricity consumption by about 8 TWh, equivalent to 5% of the current total national electricity consumption. When taking into account all current uses of electricity (including lighting, machinery, existing electric heating and cooling) this amounts to doubling of the electricity use. The use of biomass decreases electricity consumption in 2050 by 1.2 TWh to 2.6 TWh, roughly equivalent to 1 mln tonnes of fresh wood. Electricity consumption by scenario is shown on the graph below:

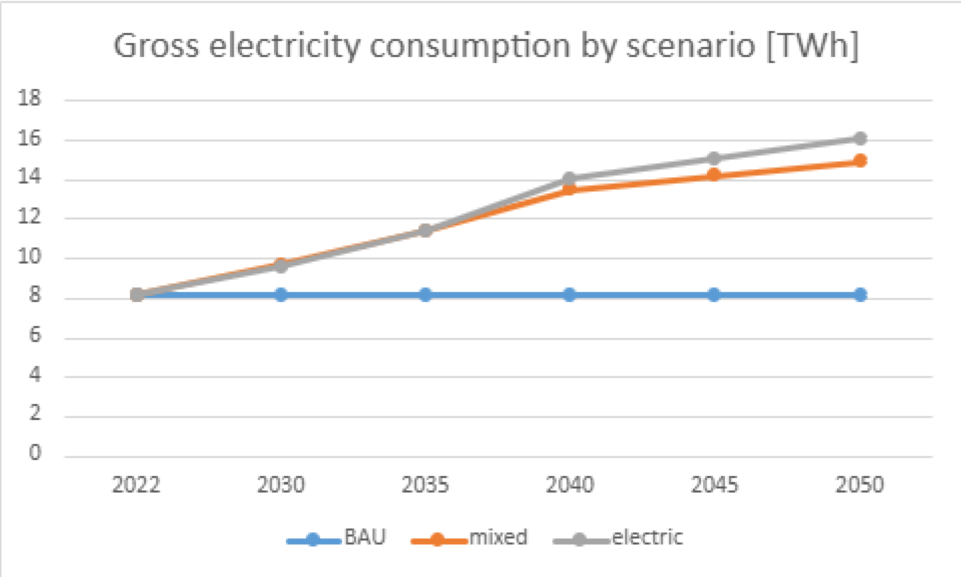


*Figure 11 Gross electricity consumption (for all uses) in food and beverages sectors by scenario*

LCOH comparison shows, that while initially cost difference for the industry does not diverge wide between scenarios, after 2035 electricity and biomass become much more competitive than fossil fuel usage. This is because natural gas and CO2 allowances are about to get more expensive, while the price of electricity will decline. The difference between BAU and other scenarios increases continuously after 2030 (the year of the energy mix divergence). This includes high capital costs and additional significant financing costs. Mixed scenario with biomass is slightly cheaper than full electrification scenario. The difference grows to 89 mln EUR by year 2050:

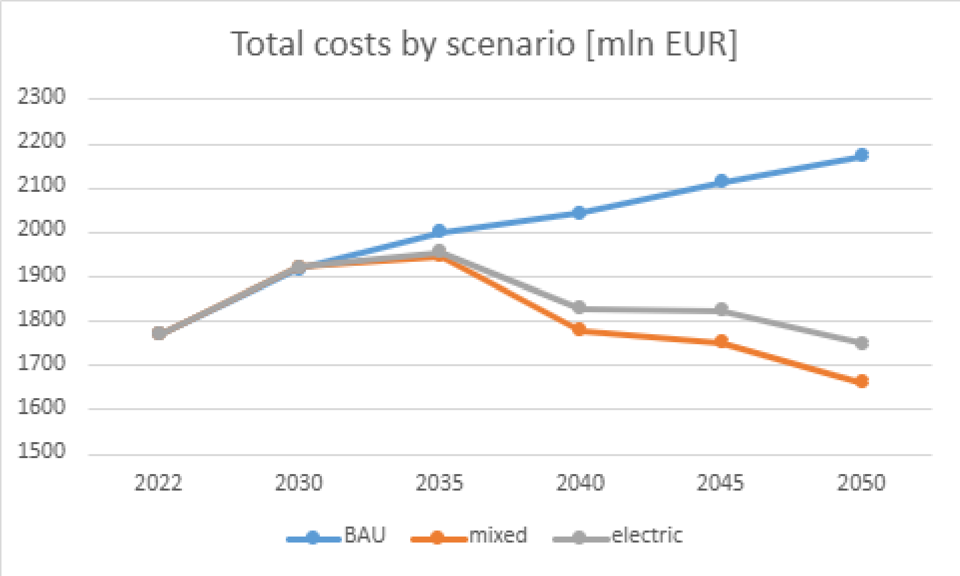


*Figure 12 Total heating costs in food and beverages sectors by scenario*

BAU scenario involves no change in the energy mix of the food and beverages industry, but decarbonization of Poland's heat and electricity mix will gradually reduce Scope 2 emissions to zero. The other two scenarios also include a gradual phase-out of directly used fossil fuels. Electric scenario has slightly higher emissions than biomass-including mixed scenario. That is because new electrified heating is responsible for Scope 2 emissions from still-not-fully decarbonized grid electricity. A comparison is shown below:

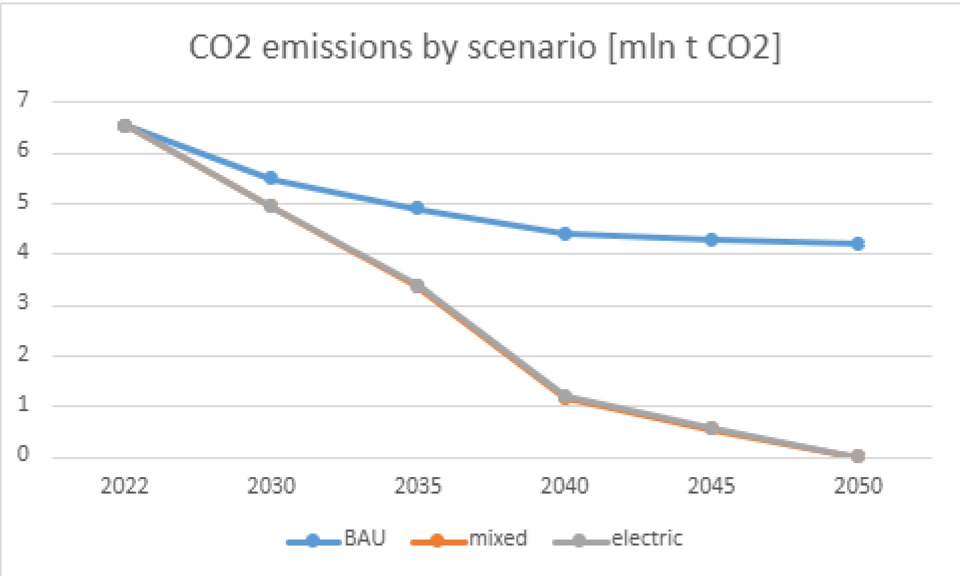


*Figure 13 Scope 1 and 2 CO2 emissions in food and beverages sectors by scenario*

It should be noted once more that access to sustainable biomass, that can truly be counted as zero-emission fuel, is limited, so even if its use is profitable, it will not become a dominant source of energy, as shown in figure 5.

# Annex 4 Electrification in paper industry

This annex shows data and calculation for pulp and paper industry. A summary of the findings can be also found in the main part of the publication.

## Data sources

Paper industry is much more standardised than food and beverage or pharmaceutical industry. Most of the products are made mostly of paper pulp which is recycled or produced from wood in a very standarised process. Production of paper pulp from wood and drying of paper are the most energy-intensive processes, accountable for most of the energy needs in the industry. Further processing, such as cutting or printing allows the few "primary" cathegories of paper change into a wide range of very diverse products. As in the case of other two sectors analysed, we have used data for year 2021 from JRC-IDEES database (Rozsai et al., 2024) and extrapolated energy use trends for year 2022 based on Eurostat sectoral data. Division of heat needs into temperature ranges was based on a study of Compass Lexecon, with constribution of the enel Foundation and ERCST.

## Current heating mix

Current heating mix is taken from JRC-IDEES database. For some of the processes the dataset shows, which energy carriers to what extent supply the demand. For conciseness and clarity, we have merged together those ways of energy use, which can be treated together from the perspective of the energy mix. Various uses of electricity, such as lighting, pumps and compressors, as well as other electric-operated machinery, are classified together as non-heat demand for electricity, which is not about to change under any scenario.

Current electric-based heating has been also treated as one category. Electric heating in paper industry is less popular and less technologically diverse than in food and beverages sector, though it plays some role particularly in secondary processes, such as printing.

Heating with other heat sources than electricity will be subject to change. Therefore it has been divided across energy carriers, wherever possible. A table with historical energy consumption in the food and beverages sector (in original units – ktoe) is presented below:

*Table 1 Current final energy mix of the paper industry (ktoe)*

| | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|
| Solids [Coal] | 185.13 | 158.53 | 171.83 | 147.70 |
| Refinery gas | 0.00 | 0.00 | 0.00 | 0.00 |
| LPG | 2.90 | 3.27 | 3.78 | 4.04 |
| Diesel oil and liquid biofuels | 14.11 | 10.36 | 18.50 | 19.78 |
| Fuel oil | 23.65 | 22.50 | 25.40 | 27.16 |
| Other liquids | 0.53 | 0.03 | 0.04 | 0.05 |

| | | | | |
|---|---|---|---|---|
| Natural gas and biogas | 239.81 | 225.05 | 239.45 | 226.12 |
| Derived gases | 0.00 | 0.00 | 0.00 | 0.00 |
| Biomass and waste | 932.74 | 977.70 | 586.04 | 672.15 |
| Ambient heat | 0.00 | 0.00 | 0.00 | 0.00 |
| Distributed steam | 58.98 | 73.21 | 90.42 | 75.11 |
| Electricity [current use] | 11.94 | 11.71 | 13.78 | 13.78 |

## Useful energy and share of each energy carrier

Final energy has been converted to useful energy by multiplying final energy consumption by efficiency of each heat generating technology, as provided in Annex 1. The result is shown in the graph below:

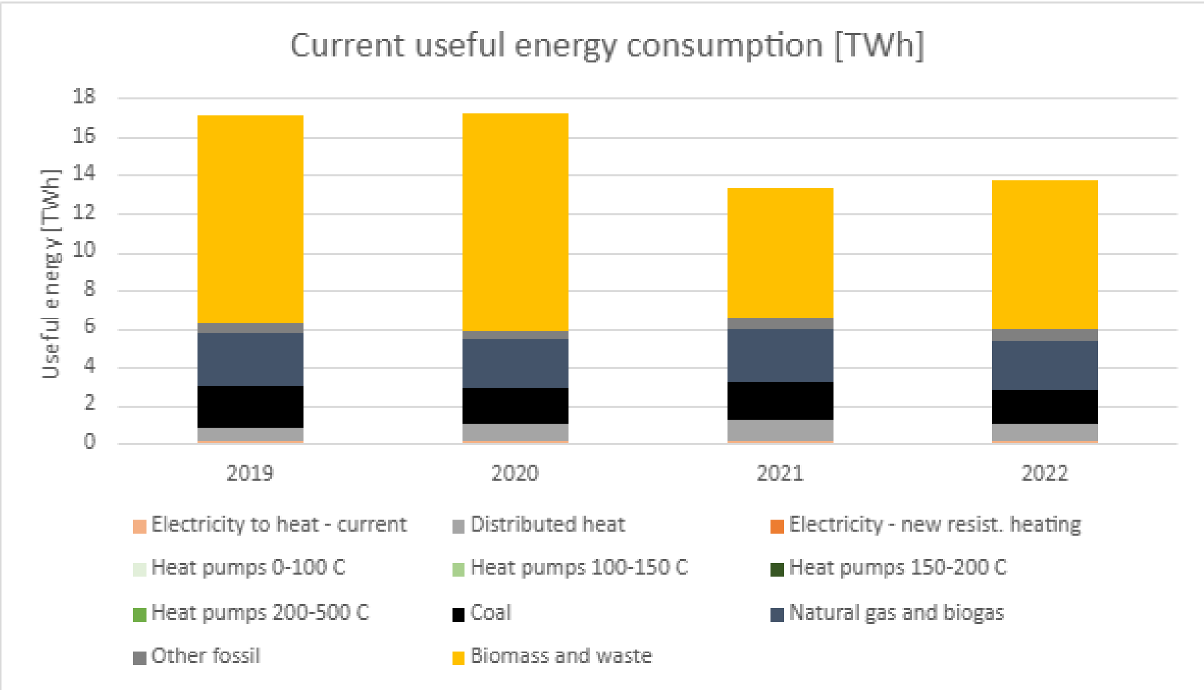


*Figure 1 Current useful energy consumption in paper industry*

Older data (not included in this study) shows, that paper industry in Poland consistently developed and increased its energy consumption until the year 2017, when it experienced a plateau of energy consumption followed by a sharp drop in 2021. This is mostly connected to external factors, such as reduced availability of cheap wood from Eastern Europe due to spiraling tensions between Russia and Belarus and the EU. Internal factors such as renovations at major pulp mills may have also been a factor. A percentage share of each energy carrier in the heating mix is shown below:

*Table 2 Current heating mix (useful energy) of the paper industry*

| | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Solids [Coal] | 12.6% | 10.7% | 15.0% | 12.5% |
| Refinery gas | 0.0% | 0.0% | 0.0% | 0.0% |
| LPG | 0.2% | 0.2% | 0.3% | 0.3% |
| Diesel oil and liquid biofuels | 1.0% | 0.7% | 1.6% | 1.7% |
| Fuel oil | 1.6% | 1.5% | 2.2% | 2.3% |
| Other liquids | 0.0% | 0.0% | 0.0% | 0.0% |
| Natural gas and biogas | 16.3% | 15.2% | 20.8% | 19.1% |
| Derived gases | 0.0% | 0.0% | 0.0% | 0.0% |
| Biomass and waste | 63.5% | 66.0% | 51.0% | 56.7% |
| Ambient heat | 0.0% | 0.0% | 0.0% | 0.0% |
| Distributed steam | 4.0% | 4.9% | 7.9% | 6.3% |
| Electricity [current use] | 0.8% | 0.8% | 1.2% | 1.2% |

## Scenarios for the future of the paper industry

The future mix of the paper industry has been shown in three scenarios. Biomass has been handed a more preferential treatment than in the food and beverage and in the chemical sector, because paper industry is already wood-oriented. Paper industry has and will have better access to primary and secondary biomass than most other sectors of the industry, therefore simple economic calculation will favour the use of biomass particularly to power and heat this industry. With that in mind, mixed scenario has been designed for large biomass use, while electric scenario shows a total electrification of the industry, while business-as-usual shows an unchanged final energy mix. Solid and liquid fossil fuels are about to be withdrawn by 2040 in the mixed and electric scenarios.

### Business-as-usual scenario

In this scenario heat demand is fulfilled using the same energy carriers as now, right until 2050. The resulting final energy mix is shown in the graph below:

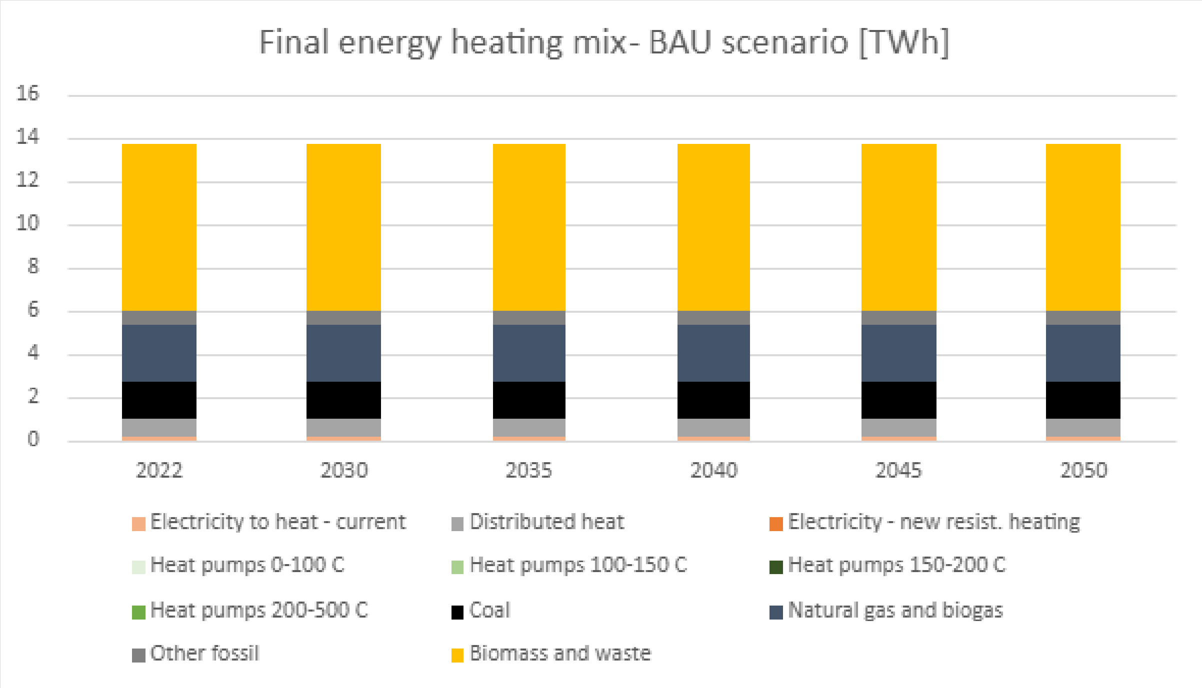


*Figure 2 Final energy mix in paper industry in BAU Scenario*

Keeping the current energy mix results in continuing high CO2 emissions. Those emissions are several times smaller than for food and beverages sector due to smaller total heat consumption and already extensive use of biomass. Overall carbon intensity of the heat mix of the paper industry would decrease due to the decarbonisation of electricity and district heat. This improvement will thus only come from decreased emissions in Scope 2.

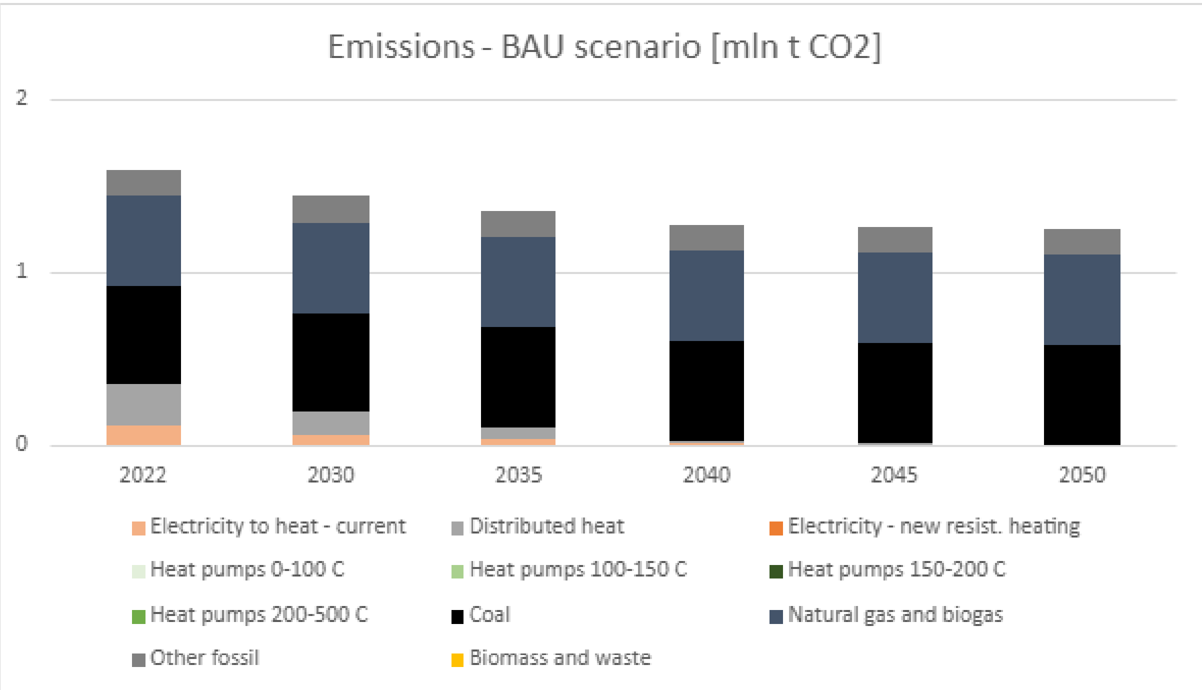


*Figure 3 CO2 emissions from Scope 1 and 2 in paper industry in BAU Scenario*

In BAU scenario keeping the current energy mix leads to consistently rising CO2 emissions costs. This increases the total expenditures for energy. The costs evolution across time is shown below:

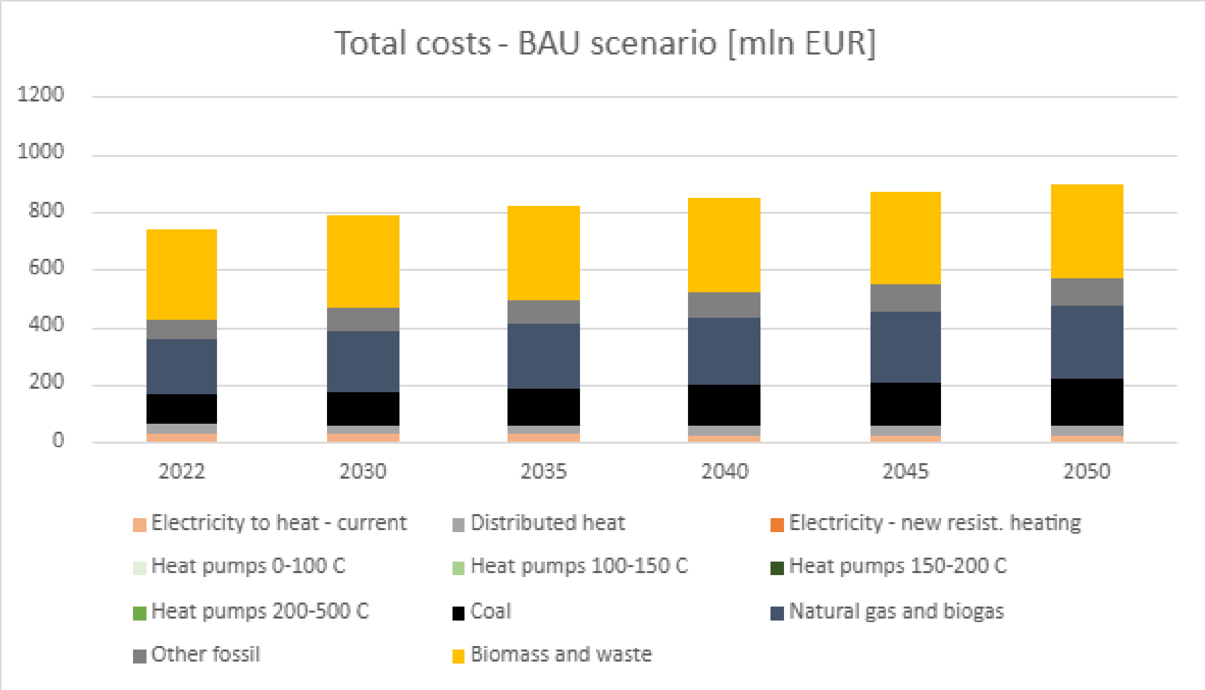


*Figure 4 Total costs of heat (LCOH) in paper industry in BAU Scenario*

## Mixed scenario

In the mixed scenario heat demand is gradually decarbonised using biomass and electricity. Coal and liquid fossil fuels are replaced until 2040 with electricity, biomass and (until 2030) natural gas. Natural gas is replaced until 2050 with electricity and biomass. No biomass is converted to electricity and no electricity is converted to biomass throughout the period. A table showing the rate of conversions in each period is shown below:

*Table 3 Share of useful energy got from each energy carrier converted into a different energy carrier before a given date in the paper industry*

| Conversion ratio until | 2022 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|
| Coal-to-gas | - | 15% | - | - | - | - |
| Coal-to-biomass | - | 15% | 10% | 40% | - | - |
| Coal-to-electric | - | 10% | 40% | 60% | - | - |
| Liquid fuels-to-gas | - | 15% | - | - | - | - |
| Liquid fuels-to-biomass | - | 15% | 10% | 40% | - | - |
| Liquid fuels-to-electric | - | 10% | 40% | 60% | - | - |
| Gas-to-biomass | - | 10% | 10% | 20% | 20% | 40% |
| Gas-to-electric | - | 10% | 15% | 30% | 30% | 60% |
| Biomass-to-gas | - | - | - | - | - | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| Biomass-to-electric | - | - | - | - | - | - |

The resulting final energy mix is shown in the graph below:

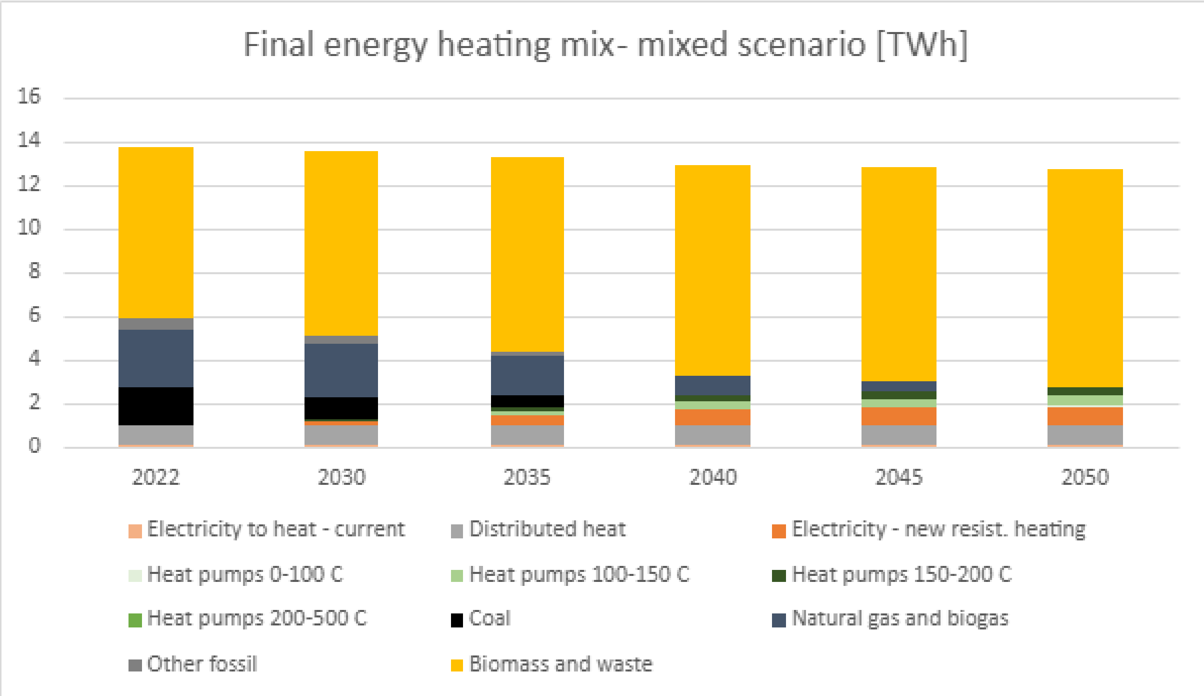


*Figure 5 Final energy mix in paper industry in mixed scenario*

Conversion from fossil fuels to electricity and biomass leads to gradual decrease in CO2 emissions. This stems both from reduced direct fossil fuels burning (Scope 1 emissions) and from the ongoing decarbonization of the imported energy (Scope 2 emissions). The results are shown below:

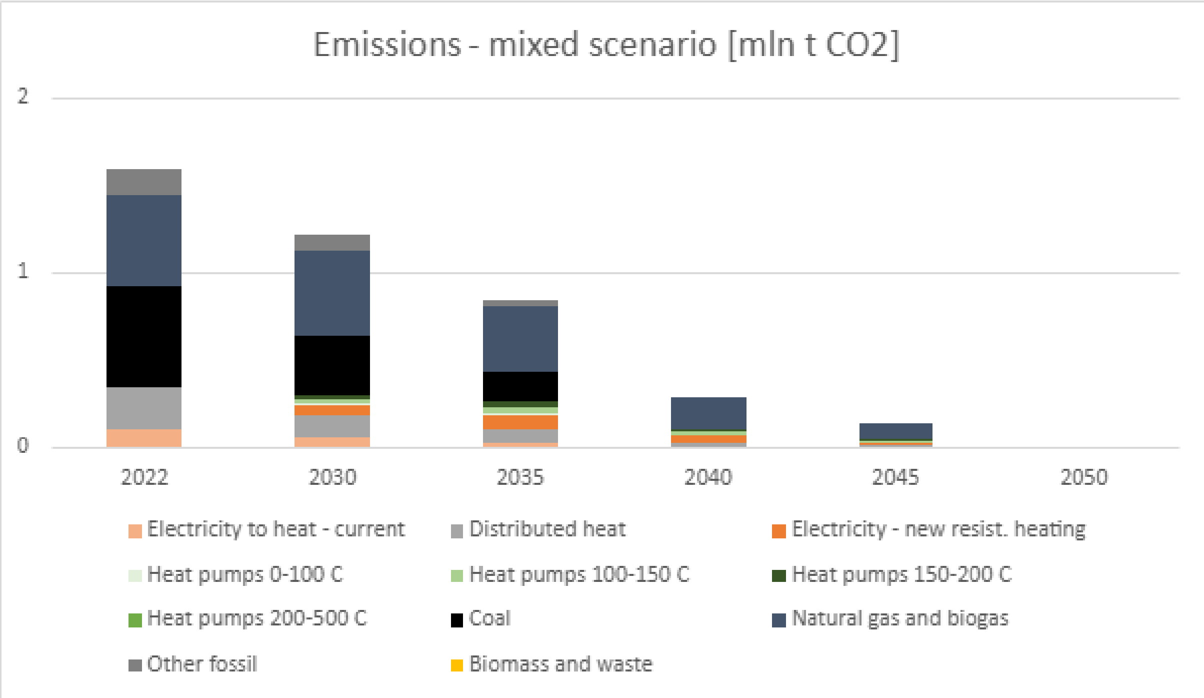


*Figure 6 CO2 emissions from Scope 1 and 2 in paper industry in mixed scenario*

Decarbonisation using primarily biomass leads to slight reduction in costs, because biomass is not burdened with $CO_2$ emission costs and not as expensive as natural gas. The results are shown below:

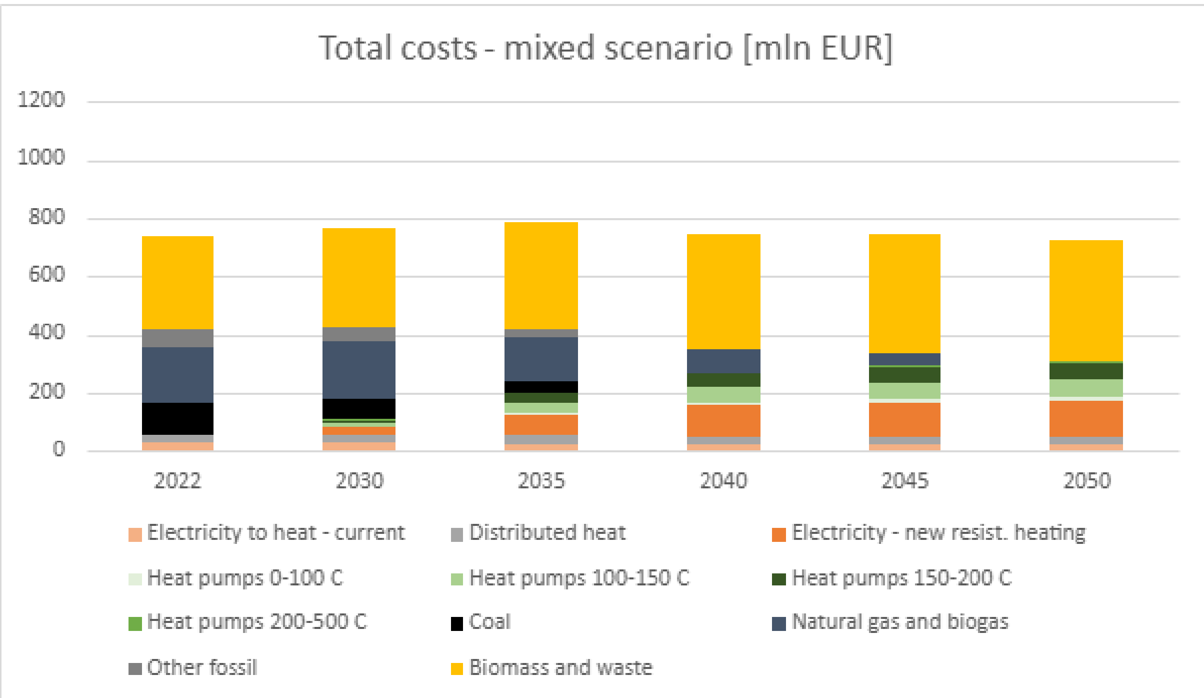


*Figure 7 Total costs of heat (LCOH) in paper industry in mixed scenario*

## Electric scenario

Electric scenario is a hypothetical full electrification of paper industry by 2050. Coal and liquid fossil fuels are replaced until 2040 with electricity, biomass and natural gas. However, in contrary to the mixed scenario, conversions to biomass are reduced after 2030 and from the 2040 biomass is on a fast phase-out trajectory, together with natural gas. This leads to an electricity-only heating mix by 2050. A table showing the rate of conversions in each period is shown below:

*Table 4 Share of useful energy got from each energy carrier converted into a different energy carrier before a given date in the paper industry*

| Conversion ratio until | 2022 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|
| Coal-to-gas | - | 15% | - | - | - | - |
| Coal-to-biomass | - | 15% | 10% | 20% | - | - |
| Coal-to-electric | - | 10% | 40% | 80% | - | - |
| Liquid fuels-to-gas | - | 15% | - | - | - | - |
| Liquid fuels-to-biomass | - | 15% | 10% | 20% | - | - |
| Liquid fuels-to-electric | - | 10% | 40% | 80% | - | - |
| Gas-to-biomass | - | 10% | 10% | - | - | - |
| Gas-to-electric | - | 10% | 15% | 50% | 50% | 100% |
| Biomass-to-gas | - | - | - | - | - | - |
| Biomass-to-electric | - | - | - | 20% | 50% | 100% |

The resulting final energy mix is shown in the graph below:

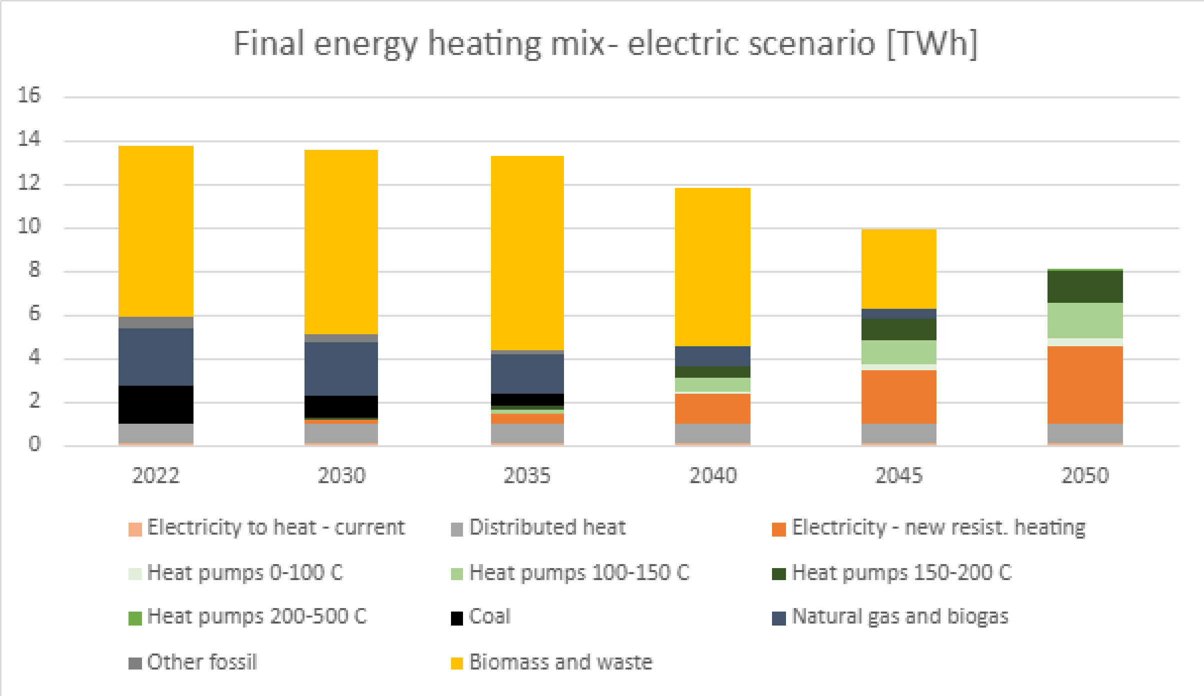


*Figure 8 Final energy mix in paper industry in electric scenario*

Conversion from fossil fuels to electricity leads to a gradual decrease in CO2 emissions. This stems both from reduced direct fossil fuels burning (Scope 1 emissions) and from the ongoing decarbonization of the imported energy (Scope 2 emissions). Since biomass is treated in this study as a zero-emission energy source, replacement of biomass with electricity does not lead to any additional CO2 emission reduction. Climate impact of the electric scenario is marginally higher than in the mixed scenario when CO2 from burning biomass is not taken into account:

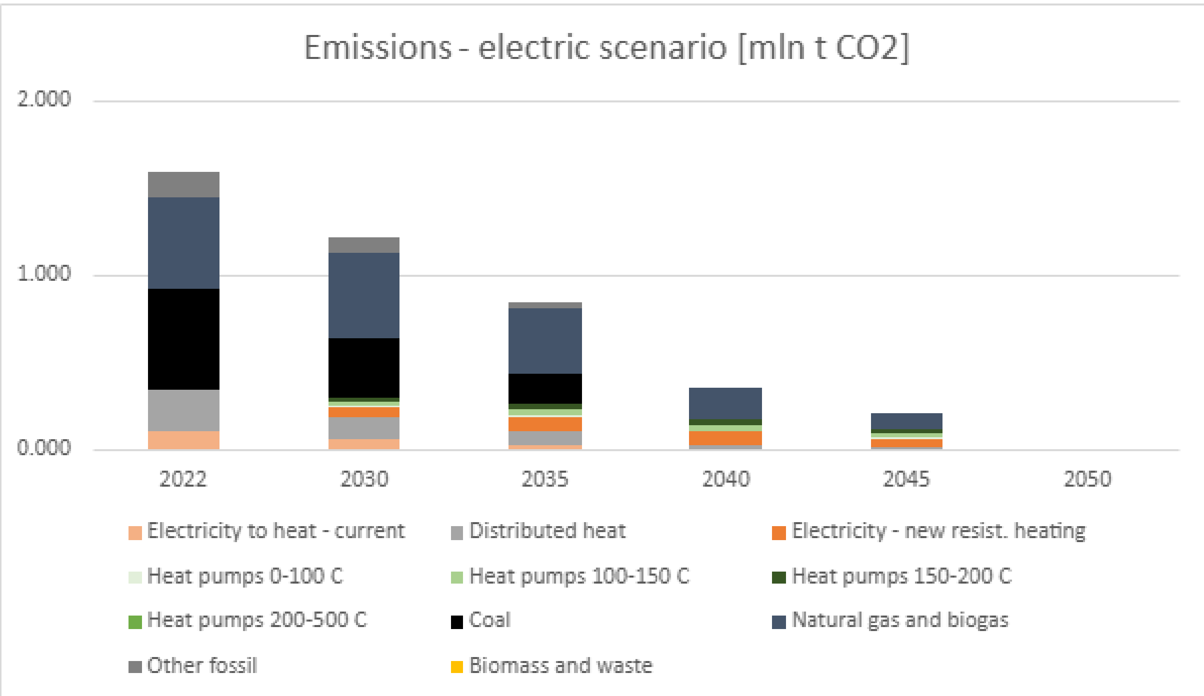


*Figure 9 CO2 emissions from Scope 1 and 2 in paper industry in electric scenario*

Electric scenario for the pulp and paper industry brings a significant increase in energy expenses. This is because electrification in the paper industry is less profitable than in the food and beverages industry due to higher required temperatures and thus smaller average efficiency of electrification. High volume of biomass to electrify leads to very high electricity consumption. The results are shown below:

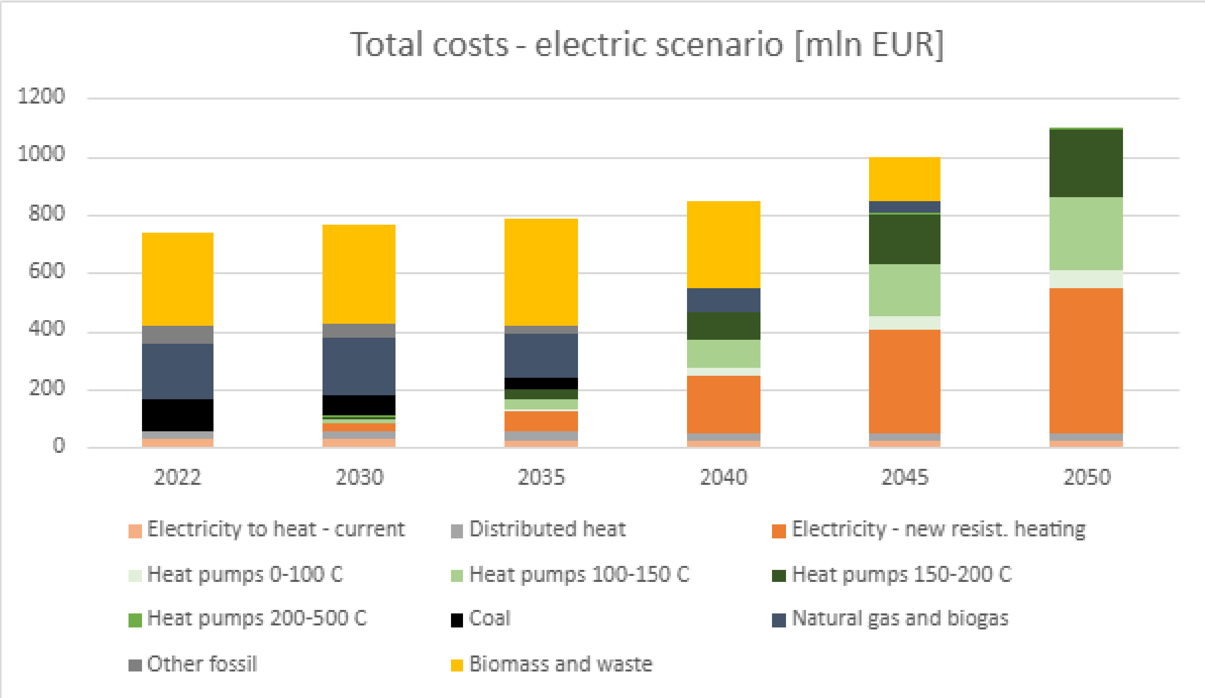


*Figure 10 Total costs of heat (LCOH) in paper industry in electric scenario*

## Scenarios summary

Full electrification of the pulp and paper industry could increase the sector's electricity consumption by about 7 TWh, equivalent to more than 4% of the current total national electricity consumption. When taking into account all current uses of electricity (including lighting, machinery, existing electric heating and cooling) it is still almost tripling of the electricity use. The use of biomass in mixed scenario allows to decrease electricity consumption in 2050 by 5.3 TWh (equivalent to 2 mln tonnes of fresh wood) with the final use of 6.6 TWh. Electricity consumption by scenario is shown on the graph below:

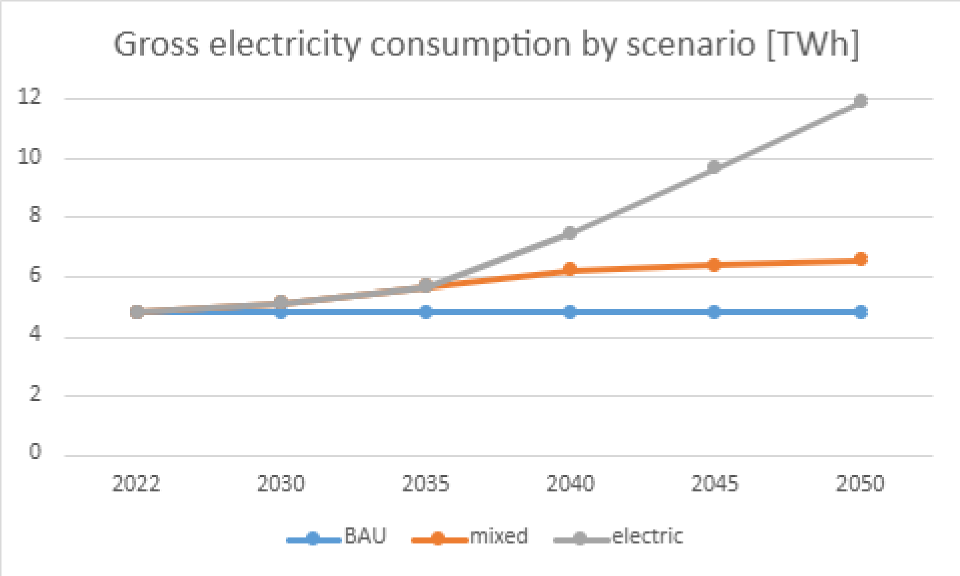


*Figure 11 Gross electricity consumption (for all uses) in paper sector by scenario*

LCOH comparison clearly shows, that expanding use of biomass is cheaper than both keeping the current heating mix and total electrification. Mixed scenario shows initially increasing cost (as all scenarios) but since 2035 total costs are reduced due to increased reliance on biomass and declining electricity price. Full electrification scenario shows drastic LCOH increase when biomass is about to be replaced with electricity, while business-as-usual scenario shows a steady increase in heating costs:

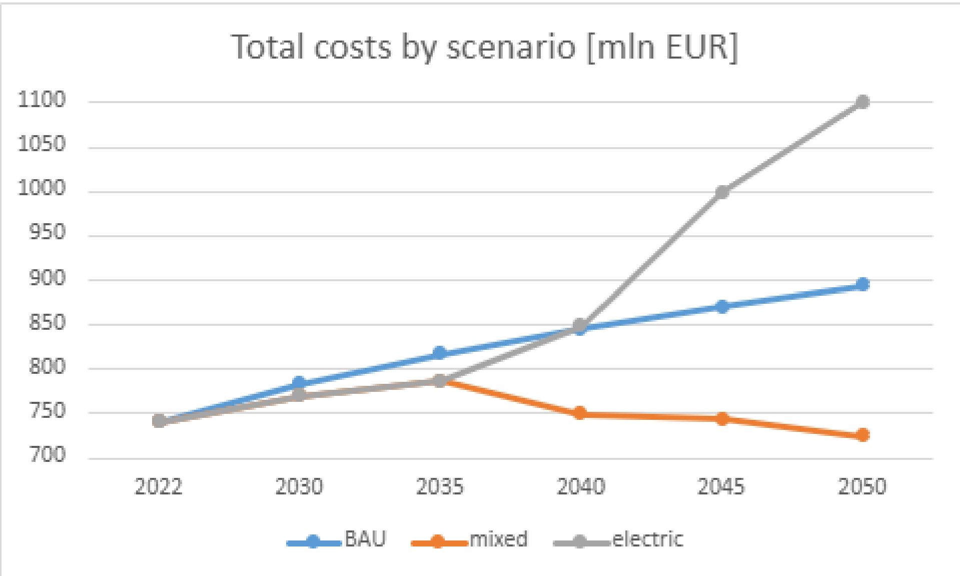


*Figure 12 Total heating costs in paper sector by scenario*

BAU scenario involves no change in the energy mix of the food and beverages industry, small reduction in the climate impact of the paper industry's energy mix will come only from decarbonization of Poland's heat and electricity mix. The other two scenarios include a gradual phase-out of directly used fossil fuels. Electric scenario has slightly higher emissions than biomass-including mixed scenario because new electrified heating is responsible for Scope 2 emissions from still-not-fully decarbonized grid electricity. A comparison is shown below:

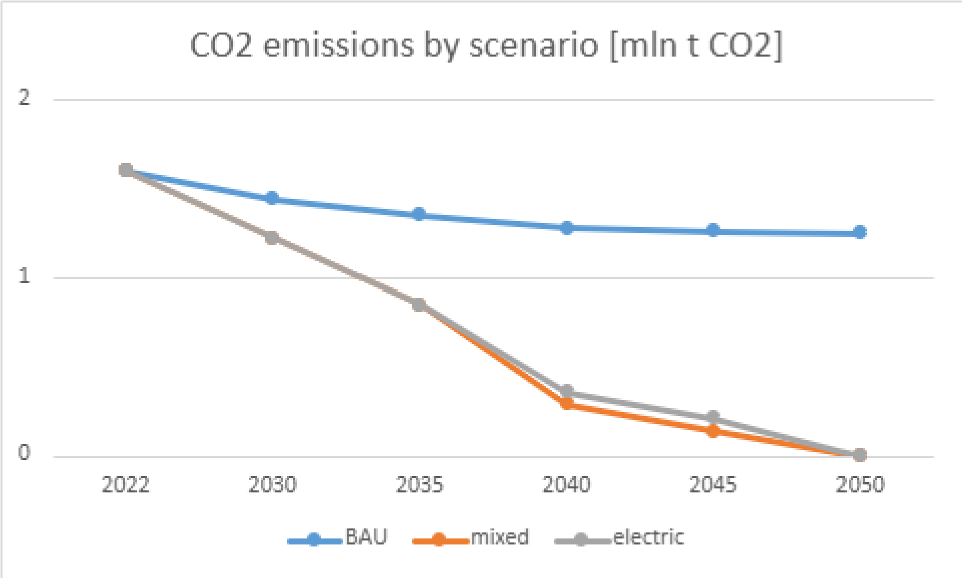


*Figure 13 Scope 1 and 2 CO2 emissions in paper sector by scenario*

It is possible that a portion of the existing, newer and more efficient biomass installations can be refurbished and supplied with sustainable biomass until 2050, as certified sustainable biomass is classified as a renewable energy source, and its combustion is not burdened with CO2 emission costs. Nevertheless, it is crucial to point out that future legislative frameworks may affect the methodology of calculating $CO_2$ emissions from biomass combustion for ETS 1 and ETS 2 systems, thus increasing the biomass installation's operational costs. Furthermore, a large increase in biomass-fired boiler capacities would cause a spike in the price of certified sustainable biomass, which in turn would increase OPEX for such installations.[6]

# Annex 5 Electrification in chemical industry

This annex shows assumptions, exemptions and results of calculations for the chemical industry.

## Data sources

Chemical industry is very concentrated and diverse at the same time. Most of the energy consumption is concentrated in a few huge factories producing a limited range of basic chemicals used as fertilisers or as feedstock the production of more advanced chemicals. These factories use a large amount of fossil fuels (mainly oil and natural gas) as feedstock. During the production process some of the feedstock (for example hydrogen atoms) are included in the product, while the rest is oxidised to cover the energy balance of the reaction. Much of the processes are conducted at very high temperatures (>300 °C), above the practical range of heat pumps.

This analysis covers only a small part of the chemical sector. The selection has been achieved by drawing data from the JRC-IDEES database (Rozsai et al., 2024) only for "Other chemicals" and "Pharmaceutical products etc." categories, while excluding "Basic chemicals" category, responsible for the majority of energy consumption. Data for 2021 and not for 2022 has been taken as a basis for this sector for 2 reasons:

- Data for 2022 is more aggregated and not as easy to divide between subsectors of the chemical industry
- 2022 was an exceptional year for the chemical industry – a price shock on natural gas market led to a drastic decline in output of several sub-branches of the industry. Domectic production in many EU countries (including Poland) has been partially substituted with import or curtailed demand.

## Current heating mix

Current consumption of energy carriers has been taken from JRC-IDEES database. For conciseness and clarity, we have merged together those ways of energy use, which can be treated together from the perspective of the energy mix. Various uses of electricity, such as lighting, pumps and compressors, as well as other electric-operated machinery, are classified together as non-heat demand for electricity, which is not about to change under any scenario. Current electric heating is also treated as a constant in further analysis.

A table with historical energy consumption in the analysed subsection of the chemical sector (in original units – ktoe) is presented below:

*Table 1 Current final energy mix of the chemical industry (ktoe)*

| | 2019 | 2020 | 2021 |
|---|---|---|---|
| Solids [Coal] | 586.35 | 540.94 | 559.47 |
| Refinery gas | 187.69 | 205.30 | 233.87 |
| LPG | 3.92 | 3.15 | 3.83 |

| | | | |
|---|---|---|---|
| Diesel oil and liquid biofuels | 23.25 | 21.80 | 4.00 |
| Fuel oil | 3.28 | 2.37 | 2.99 |
| Other liquids | 0.14 | 0.05 | 0.04 |
| Natural gas and biogas | 179.83 | 203.99 | 227.32 |
| Derived gases | 6.89 | 3.04 | 5.87 |
| Biomass and waste | 9.06 | 8.09 | 7.87 |
| Ambient heat | 0.00 | 0.00 | 0.00 |
| Distributed steam | 164.03 | 173.39 | 171.83 |
| Electricity [current use] | 35.41 | 35.12 | 27.82 |

Division into different temperature ranges has been approximated using a simplified method – a share of low-temperature (<100°C) heat has been taken from JRC-IDEES database, where it is selected as a separate cathegory. This heat demand is rather small – only 3% of the total. High-temperature (>500°C) heat share was taken from the same source – it is the value for "ovens". The rest of the heat demand has been divided equally into three temperature ranges between 100°C and 500°C.

## Useful energy and share of each energy carrier

Final energy has been converted to useful energy by multiplying final energy consumption by efficiency of each heat generating technology. Details and coefficients are provided in Annex 1. The result is shown in the graph below:

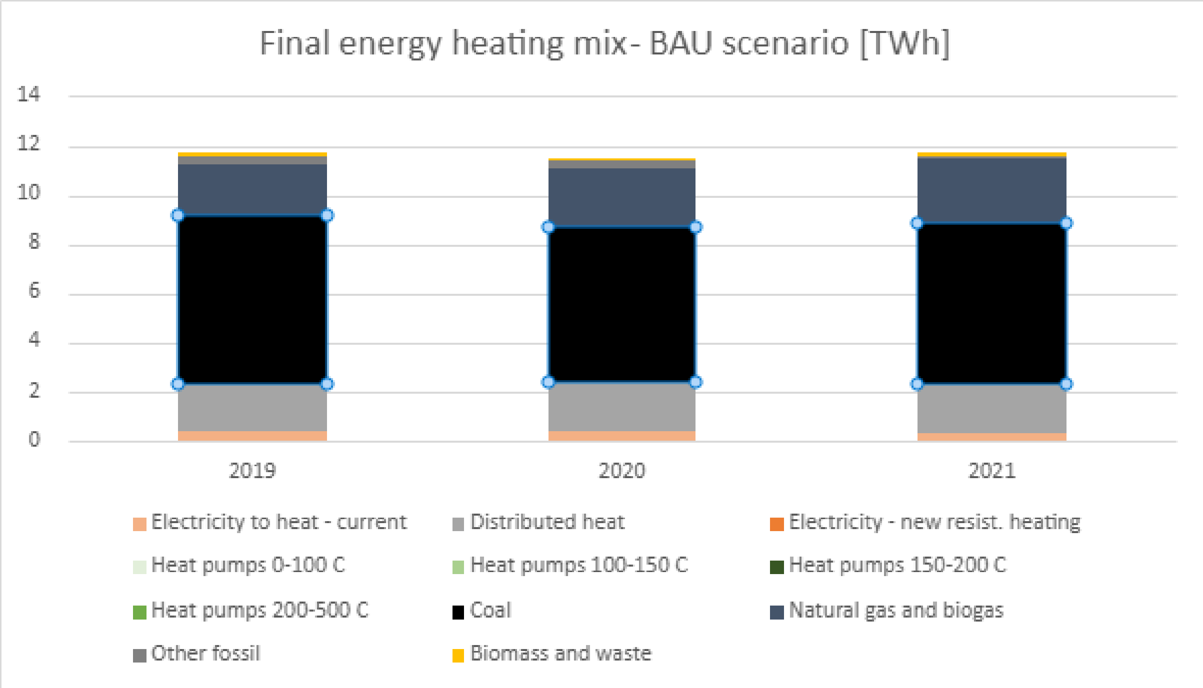


*Figure 1 Current useful energy consumption in chemical industry*

Older data (not included in this study) shows, that "Other chemicals" industry shows a significant variation in energy demand across time, with a low of 488 ktoe in 2022 and values above 1300 ktoe for years 2001, 2009-10 and since 2018. "Pharmaceutical products etc." show a steady increase in energy use since 2001.

*Table 2 Current heating mix (useful energy) of the chemical industry*

| | 2019 | 2020 | 2021 |
|---|---|---|---|
| Solids [Coal] | 48.9% | 45.2% | 44.9% |
| Refinery gas | 15.6% | 17.1% | 18.8% |
| LPG | 0.3% | 0.3% | 0.3% |
| Diesel oil and liquid biofuels | 1.9% | 1.8% | 0.3% |
| Fuel oil | 0.3% | 0.2% | 0.2% |
| Other liquids | 0.0% | 0.0% | 0.0% |
| Natural gas and biogas | 15.0% | 17.0% | 18.3% |
| Derived gases | 0.6% | 0.3% | 0.5% |
| Biomass and waste | 0.8% | 0.7% | 0.6% |
| Ambient heat | 0.0% | 0.0% | 0.0% |
| Distributed steam | 13.7% | 14.5% | 13.8% |
| Electricity [current use] | 3.0% | 2.9% | 2.2% |

## Scenarios for the future of the chemical industry

The future of the energy mix of the chemical sector (excluding basic chemicals) has been proposed in three different scenarios.

### Business-as-usual scenario

In this scenario heat demand is fulfilled using the same energy carriers as now, right until 2050. There are no changes even for the "refinery gas", assuming, that the refinery sector remains at the current path as well. The resulting final energy mix is shown in the graph below:

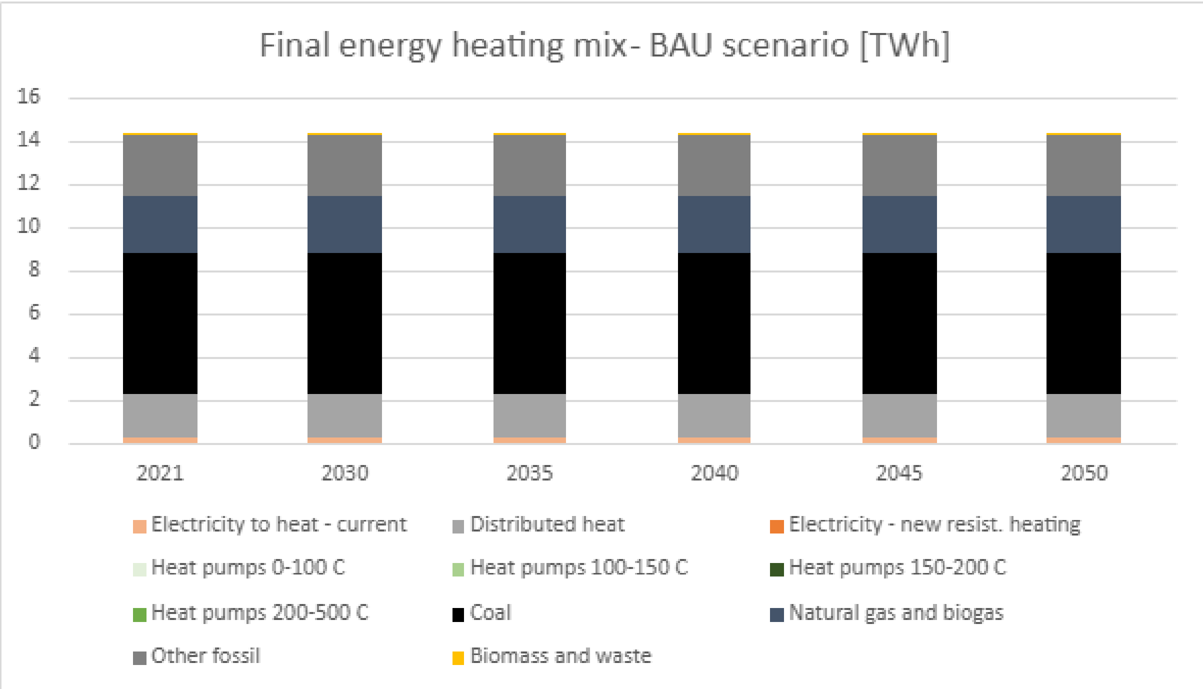


*Figure 2 Final energy mix in chemical industry in BAU Scenario*

Keeping the current energy mix results in continuing high CO2 emissions, particularly from coal. Overall carbon intensity of the heat mix of the chemical industry would decrease due to the decarbonisation of electricity and district heat. This improvement will thus only come from decreased emissions in Scope 2.

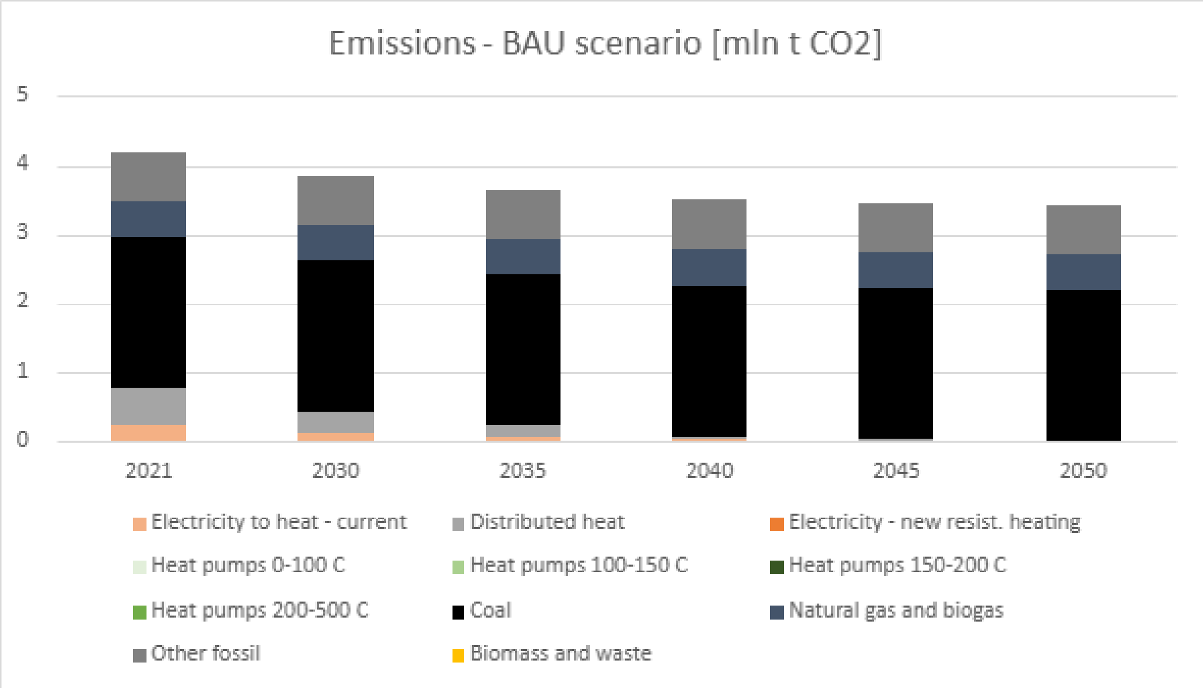


*Figure 3 CO2 emissions from Scope 1 and 2 in chemical in BAU Scenario*

In BAU scenario keeping the current energy mix leads to consistently rising $CO_2$ emissions costs. This adds to the energy price, which is relatively low and to low investment and operational costs of fossil fuel boilers. The costs evolution across time is shown below:

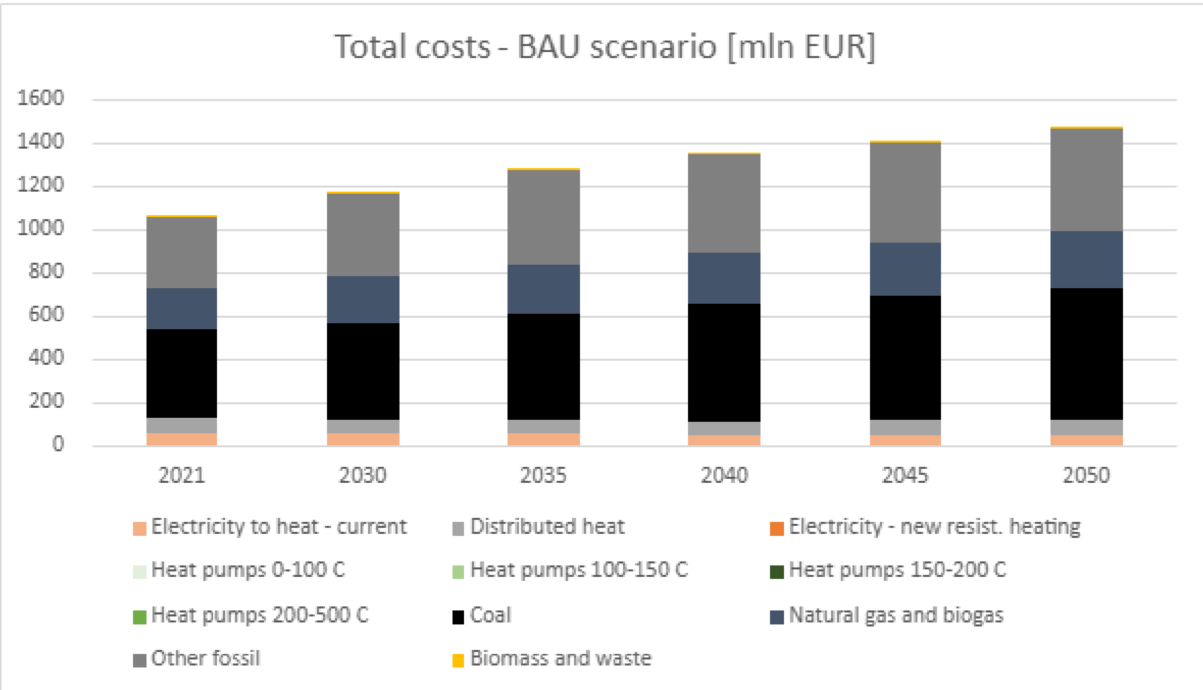


*Figure 4 Total costs of heat (LCOH) in chemical industry in BAU Scenario*

## Mixed scenario

In the mixed scenario heat demand is gradually decarbonised using electrification. Until 2030 some of demand for solid and liquid fossil fuels is satisfied with biomass. Coal and liquid fossil fuels are completely replaced until 2040. Natural gas is replaced until 2050 mainly with electricity, with a small share of biomass. The use of biomass is smaller than in mixed scenarios for food and beverage and for paper industry, since the chemical industry has less natural synergy with biomass than the previous two, resulting in less organic waste and higher distances from factories to sources of sustainable biomass. Refinery gas is about to be withdrawn at the same rate as natural gas. A table showing the conversion rate in each period is shown below:

*Table 3 Share of useful energy got from each energy carrier converted into a different energy carrier before a given date in the food and beverages industry*

| Conversion ratio until | 2022 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|
| Coal-to-gas | - | 20% | - | - | - | - |
| Coal-to-biomass | - | - | 5% | 10% | - | - |
| Coal-to-electric | - | 20% | 45% | 90% | - | - |
| Liquid fuels-to-gas | - | 20% | - | - | - | - |
| Liquid fuels-to-biomass | - | - | 5% | 10% | - | - |
| Liquid fuels-to-electric | - | 20% | 45% | 90% | - | - |
| Gas-to-biomass | - | - | - | 5% | 5% | 10% |
| Gas-to-electric | - | 20% | 25% | 45% | 45% | 90% |
| Biomass-to-gas | - | - | - | - | - | - |
| Biomass-to-electric | - | - | - | - | - | - |

The resulting final energy mix is shown in the graph below:

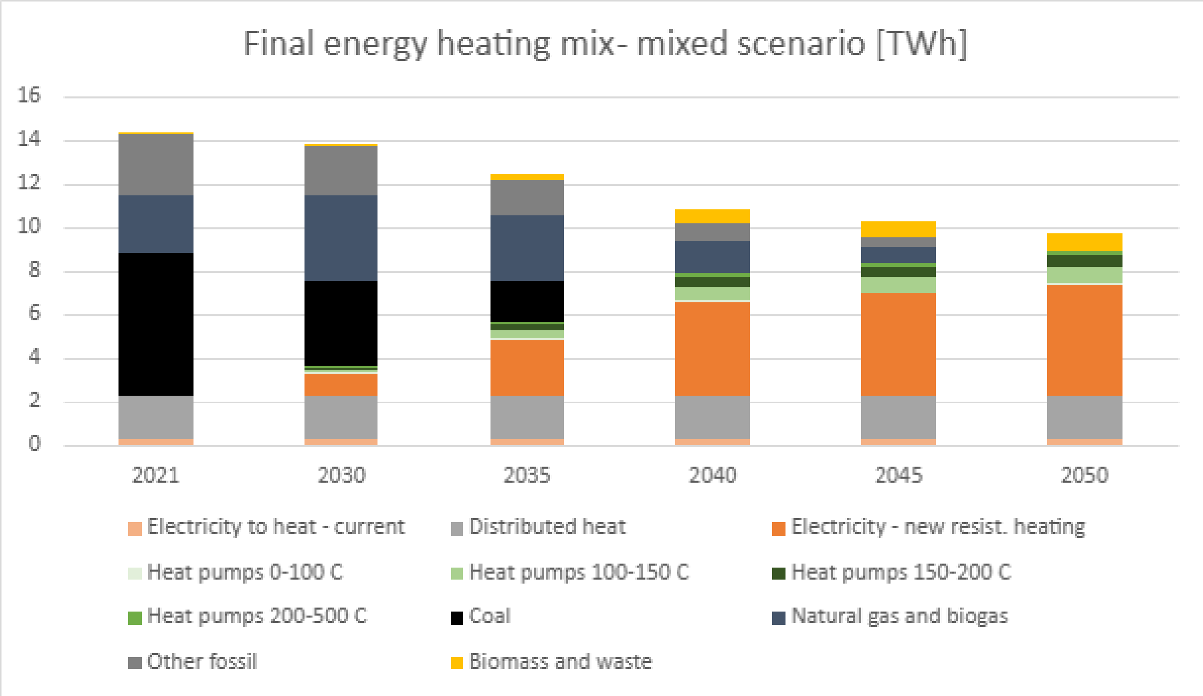


*Figure 5 Final energy mix in chemical industry in mixed scenario*

Conversion from fossil fuels to electricity with a small biomass share leads to a gradual decrease in CO2 emissions. This stems both from reduced direct fossil fuels burning (Scope 1 emissions) and from the ongoing decarbonization of the imported energy (Scope 2 emissions). The results are shown below:

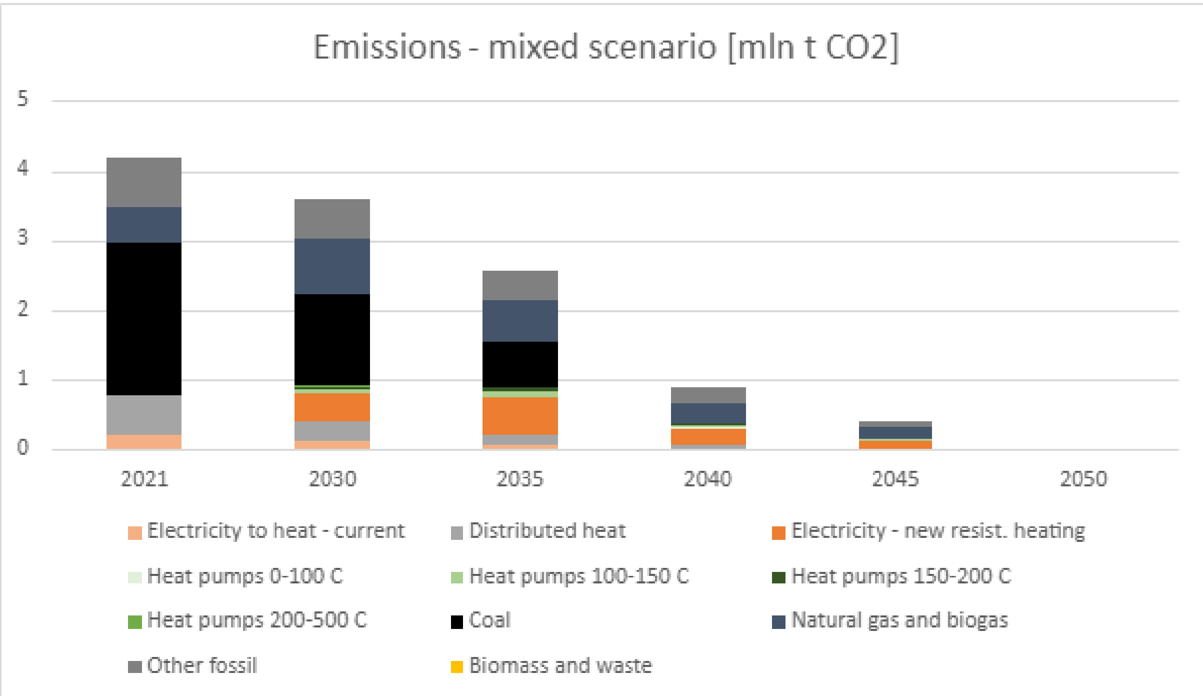


*Figure 6 CO2 emissions from Scope 1 and 2 in chemical industry in mixed scenario*

Mixed scenario leads to a gradual reduction in CO2 emission costs. In the interim (2030 and 2035), costs are higher, because greater use of electricity leads to higher operating costs. However, after 2035 decarbonisation leads to decreasing costs. In reality, higher interim costs can be abated by using most effective electricification (with the use of heat pumps) wherever possible first, leaving harder or less economical to electrify applications for the time, when electricity will be cheaper and CO2 costs higher.

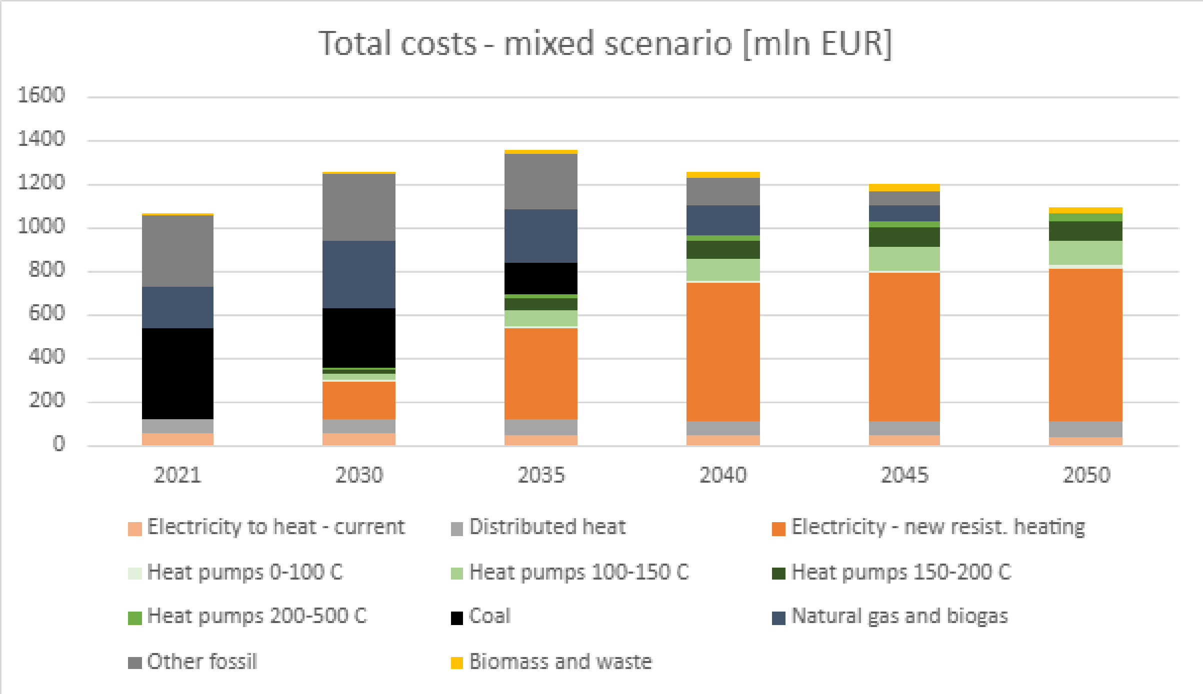


*Figure 7 Total costs of heat (LCOH) in chemical industry (part of) in a mixed scenario*

## Electric scenario

Electric scenario shows the effects of full electrification of the analysed part of the chemical industry by 2050. Coal and liquid fossil fuels are replaced until 2040 with electricity and (until 2030) natural gas. Biomass is not used as a replacement fuel and is gradually phased out by 2050. This leads to an electricity-only heating mix by 2050. A table showing the rate of conversions in each period is shown below:

*Table 4 Share of useful energy got from each energy carrier converted into a different energy carrier before a given date in the chemical industry*

| Conversion ratio until | 2022 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|
| Coal-to-gas | - | 20% | - | - | - | - |
| Coal-to-biomass | - | - | - | - | - | - |
| Coal-to-electric | - | 20% | 50% | 100% | - | - |
| Liquid fuels-to-gas | - | 20% | - | - | - | - |
| Liquid fuels-to-biomass | - | - | - | - | - | - |
| Liquid fuels-to-electric | - | 20% | 50% | 100% | - | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| Gas-to-biomass | - | - | - | - | - | - |
| Gas-to-electric | - | 20% | 25% | 50% | 50% | 100% |
| Biomass-to-gas | - | - | - | - | - | - |
| Biomass-to-electric | - | 10% | 10% | 20% | 50% | 100% |

The resulting final energy mix is shown in the graph below:

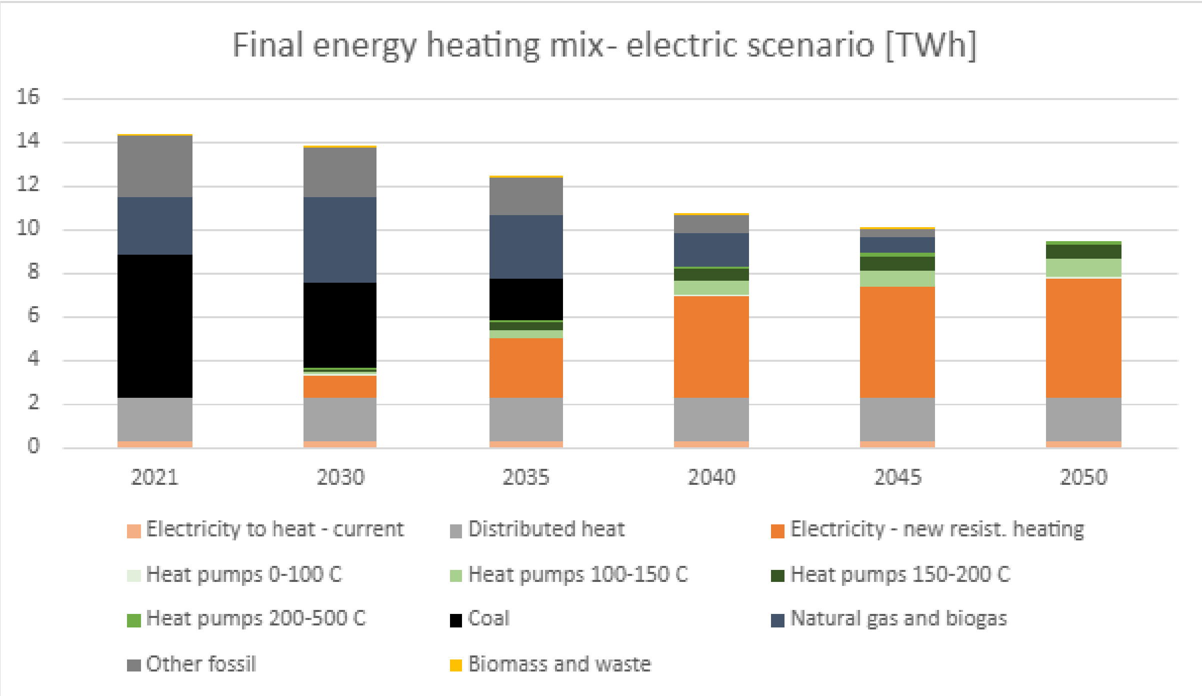


*Figure 8 Final energy mix in chemical industry (part of) in electric scenario*

Conversion from fossil fuels to electricity leads to a gradual decrease in CO2 emissions. This stems both from reduced direct fossil fuels burning (Scope 1 emissions) and from the ongoing decarbonization of the imported energy (Scope 2 emissions). As in the case of the other two industries, climate impact of the electric scenario is marginally higher than in the mixed scenario when CO2 from burning biomass is not taken into account:

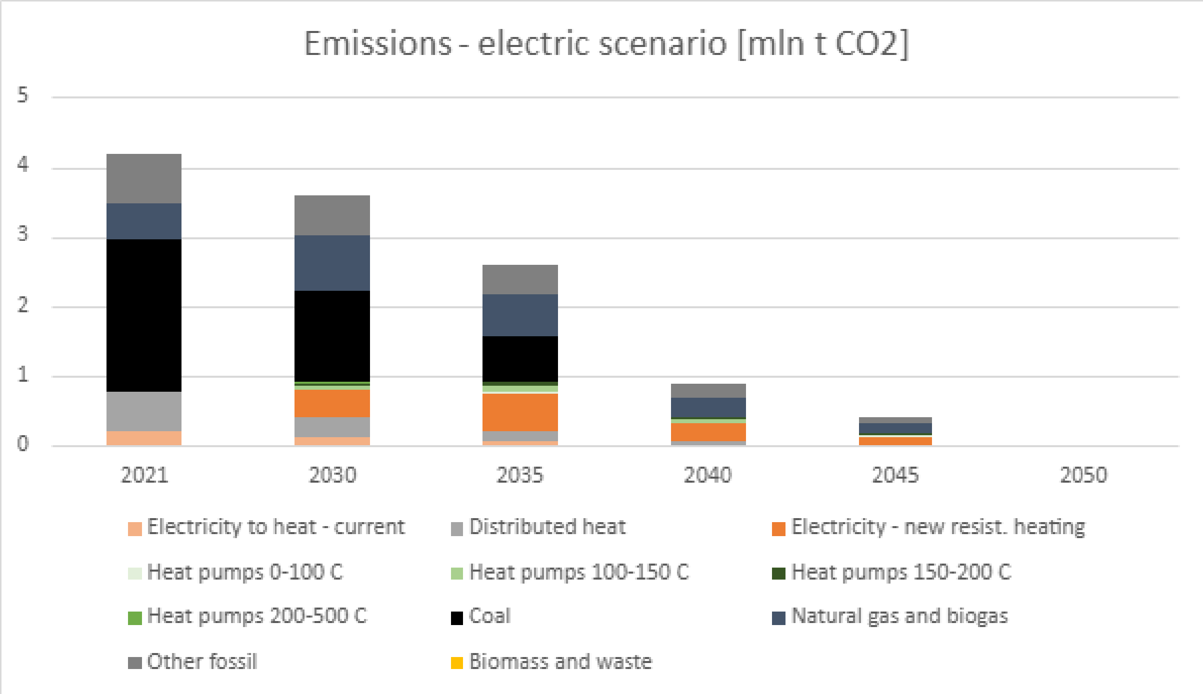


*Figure 9 CO2 emissions from Scope 1 and 2 in chemical industry (part of) in electric scenario*

Electric scenario leads finally to zero CO2 emission cost, however since electricity is more expensive than biomass, total costs of heat are slightly higher than in mixed scenario. The difference is very small owing to a small use of biomass in mixed scenario. The results are shown below:

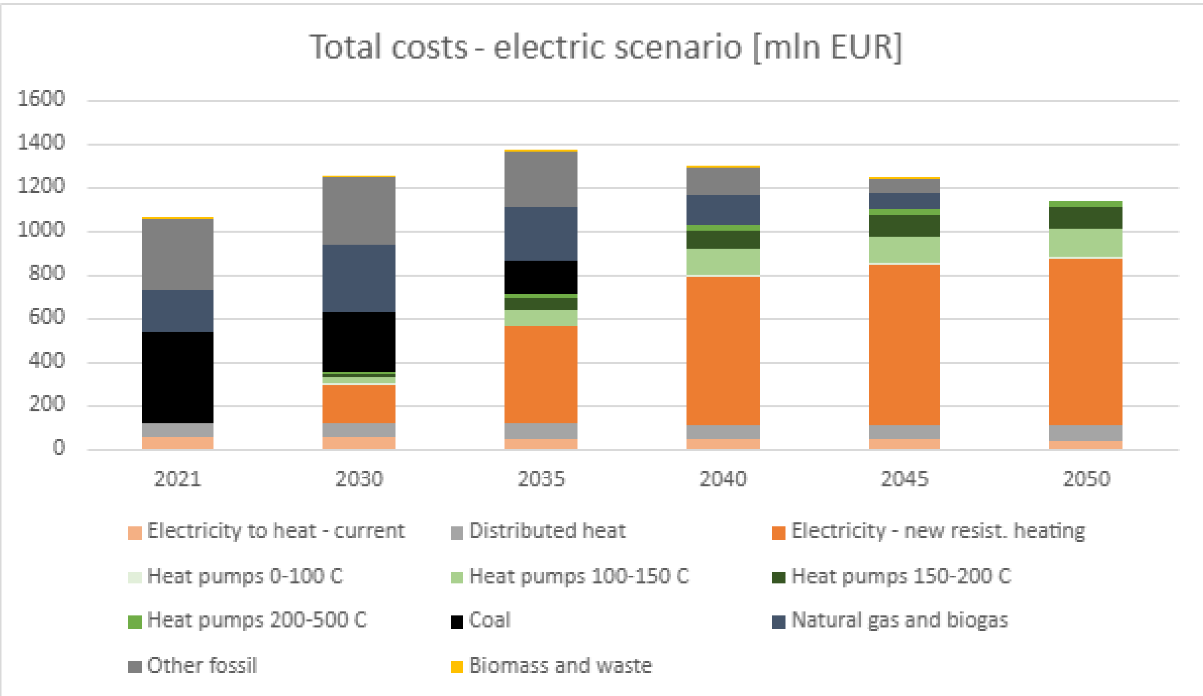


*Figure 10 Total costs of heat (LCOH) in chemical industry (part of) in electric scenario*

## Scenarios summary

Full electrification of these parts of the chemical industry could increase the sector's electricity consumption by about 7 TWh,, more than 4% of the current total national electricity consumption. When taking into account all current uses of electricity (including lighting, machinery, existing electric heating and cooling) this amounts to almost tripling of the electricity use. The use of biomass in the mixed scenario decreases electricity consumption in 2050 by 0.5 TWh compared with the electric scenario, with the final use of 0.8 TWh of biomass, roughly equivalent to 300 th. tonnes of fresh wood. These numbers are of course many times smaller, than if the "Basic chemicals" sector has been taken into account as well. Electricity consumption by scenario is shown on the graph below:

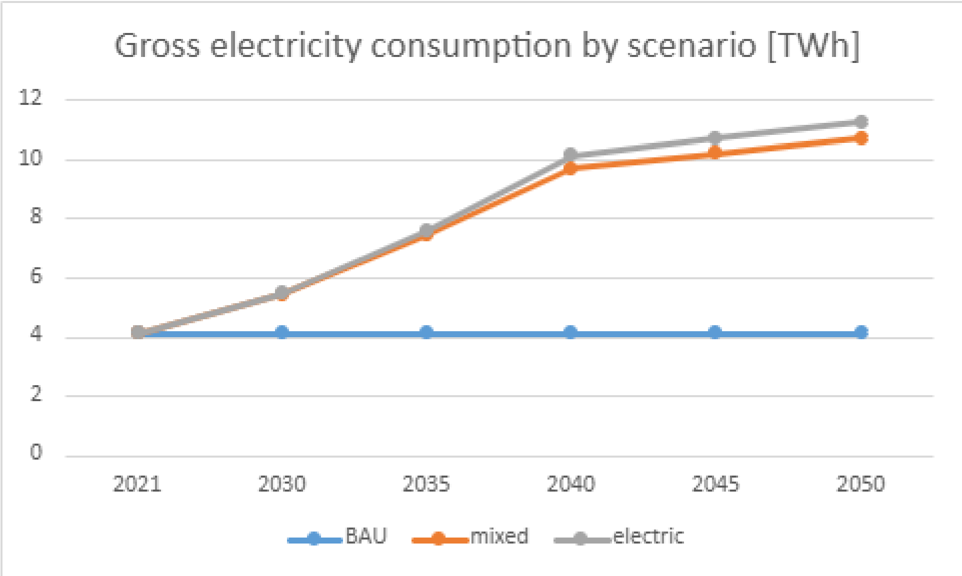


*Figure 11 Gross electricity consumption (for all uses) in chemical sectors by scenario*

LCOH comparison shows, that decarbonisation using electricity and (in the interim) natural gas leads first to a notable increase in cost, but then to cost reduction compared to BAU scenario. This is because natural gas and CO2 allowances are about to get more expensive, while the price of electricity will decline. The difference between BAU and other scenarios increases with the progress of electrification of the industry and decarbonisation of the electricity mix. Mixed scenario with biomass is slightly cheaper than fully electric scenario. The cost comparison is shown below:

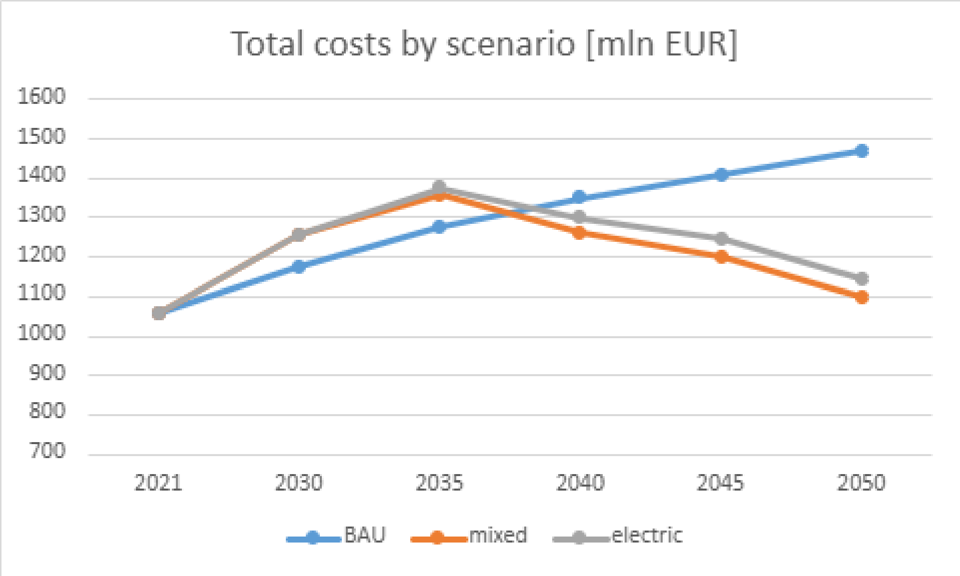


*Figure 12 Total heating costs (LCOH) in chemical sector (part of) by scenario*

BAU scenario involves no change in the energy mix of the analysed part of the chemical industry, but decarbonization of Poland's heat and electricity mix will gradually reduce Scope 2 emissions to zero. Other two scenarios also include a gradual phase-out of directly used fossil fuels. Fully electrified scenario has slightly higher emissions than biomass-including mixed scenario. That is because new electrified heating is responsible for Scope 2 emissions from still-not-fully decarbonized grid electricity. A comparison is shown below:

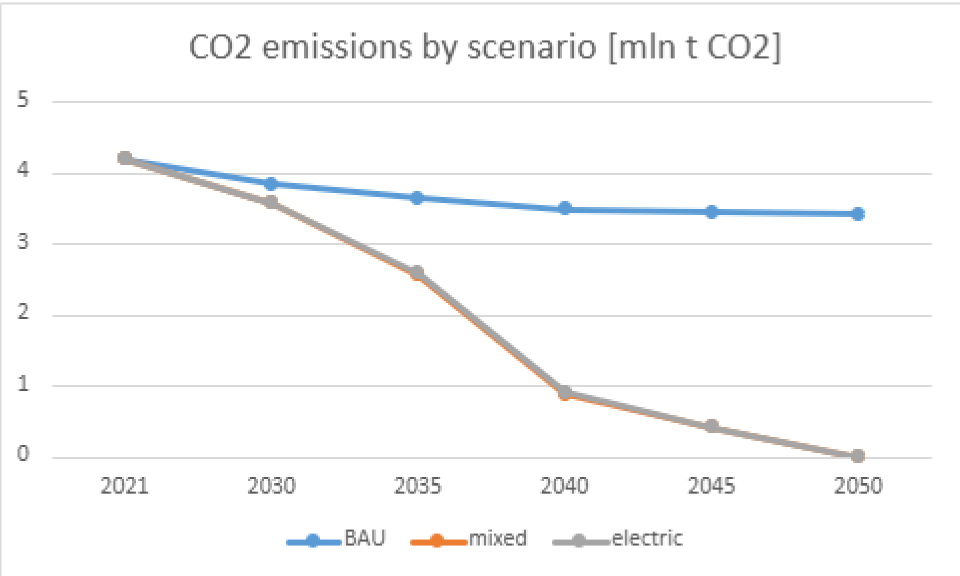


*Figure 13 Scope 1 and 2 CO2 emissions in chemical sectors by scenario*

Biomass should not be treated as a preferred energy carrier of the industry. Even if the mixed scenario involves a relatively minor conversion into biomass use, biomass use in 2050 is by an order of magnitude higher than in 2021. The use of biomass can however bring financial incentives if it is available in sufficient quantity, and its use will be treated as carbon-neutral.

# Annex 6 – Planned measures for industry

*Table 20 Overview of measures according to draft of National Energy and Climate Plan (NECP)*

| Measure | Description |
|---|---|
| Measure 14 – Priority instrument by NFOŚiGW - "regional district heating" | The programme includes projects for the reduction of greenhouse gas emissions (investment in RES for heat production), the expansion of district heating systems and the replacement of privately owned high-carbon heat sources. |
| Measure 15 - Priority instrument by NFOŚiGW - "RES as a heat source for district heating" | Investments concerning the construction and/or reconstruction of heating plants with a total installed capacity of at least 2 MWt, which use: heat pumps, solar collectors or geothermal energy to produce heat. Support can also be obtained from the programme for energy storage facilities. Only installations from which at least 70% of the usable heat generated in the RES unit in a calendar year will be fed into the public heating network can be subsidised. |
| Measure 17 Financial Instrument - Other NFOŚiGW programmes for RES development | The measure covers the co-financing of projects aimed at the construction or modernisation of electricity systems to enable their connection to RES, and the construction or modernisation of RES units, other than those mentioned above, of a regional or individual nature. |
| Measure 26 Securing conditions for SMR development. | The measure consists of the provision of conditions for the commissioning and operation of small-scale modular nuclear reactors by private entities including, inter alia: human resources and competence development, building public awareness and strengthening the potential of Polish industry. |
| Measure 73 Financial instrument - energy-intensive industry | The measure concerns support to improve energy efficiency in energy-intensive industries covered by the EU Emissions Trading Scheme (EU ETS) and to decarbonise by increasing electricity generation from RES. |
| Measure 75 Financial instrument - contract for difference for industrial hydrogen production | The contract for difference is to provide public aid in the form of a predetermined surcharge on the price of 1 kg of hydrogen produced by a producer and used by a consumer in Poland. The surcharge is to reduce the difference between the price of renewable hydrogen and so-called grey hydrogen (obtained from fossil fuels). On the other hand, |

| Measure | Description |
|---|---|
| | ensuring that the price of renewable hydrogen is at a level that allows it to compete on the market with grey hydrogen, i.e. removing the risk associated with the still early stage of development of the technology and production of renewable hydrogen, should reduce the risk of Polish hydrogen projects and contribute to the development of the renewable hydrogen market in Poland. The mechanism is expected to facilitate the replacement, mainly in industry, the so-called grey hydrogen with renewable hydrogen. |
| Measure 76 Supporting the construction of renewable and low-carbon hydrogen production capacity | The measure aims to financially support the construction of low-emission and renewable hydrogen production in Poland. Funding for the measure will be allocated from the NGEU. |
| Measure 77 Analysis regarding the need for an offshore terminal for ammonia handling | In view of the growing demand for renewable hydrogen and green ammonia, the measure aims to determine whether there is a need for a marine port terminal to handle imported hydrogen together with an ammonia cracking infrastructure. The analysis is intended to answer the question of whether the construction of such a terminal will be justified and will benefit the Polish economy. |
| Measure 79 Contracts for difference for CO2 reduction and research, education and commercial projects on CCS and CCUS | This action includes the preparation of a financial support instrument for CO2 emission reduction installations (contracts for difference). It is a proven instrument in promoting large-scale industrial installations such as CCS, CCU or hydrogen production. The activity also includes other activities to support CO2 capture and utilisation (CCU) technology and the construction and operation of carbon capture and storage (CCS) facilities, including research, education projects. |
| Measure 91 Financial instrument - Preferences for generators of electricity from high-efficiency cogeneration | The measure consists of providing facilities for cogeneration units by facilitating the connection to the electricity grid. It aims to both stimulate the construction of new cogeneration units and to maintain electricity production from high-efficiency cogeneration in existing units. With the new state aid guidelines in force In view of the new Climate, Energy and Environmental Aid Guidelines (CEEAG) issued by the European Commission, which do not provide for support for fossil fuels, and in particular carbon-based fuels, support for carbon-based fuels should be completely discontinued. |

| Measure | Description |
| --- | --- |
| Measure 92 Financial instrument - Cogeneration premium | The instrument consists of providing subsidies for the energy produced in high-efficiency cogeneration, obtained through auctions. Its purpose is both to stimulate the construction of new cogeneration units, as well as to maintain the production of electricity from high-efficiency cogeneration in existing units which, without support, would not be able to operate due to a financial gap in operating costs. |
| Measure 93 Financial instrument - Other NFOŚiGW programmes supporting the development of cogeneration | The measure covers the co-financing of projects aimed at the construction or modernisation of district heating systems and the construction or modernisation of units producing heat and electricity in high-efficiency cogeneration. |
| Measure 94 Financial instrument - white certificates scheme | Certificates confirming that a certain amount of energy has been saved as a result of investments aimed at improving energy efficiency of the economy, increasing energy savings by end users, reducing losses of electricity, heat or natural gas in transmission or distribution. The certificates have property rights and are traded on the Polish Power Exchange (TGE). |
| Measure 95 Development of energy audits and energy management systems. | The measure consists of assessing the amount and structure of the energy consumed and recommending specific solutions for improving energy efficiency to determine their cost-effectiveness. In addition, it includes advice on undertaking and implementing investments in energy efficiency. |
| Measure 99 Support for ESCOs | The measure aims at taking activities to support companies operating in the field of energy efficiency and RES with a preference for companies that are providers of energy services. |
| Measure 112 Development of hydrogen infrastructure | The measures aim to support investment in the development of hydrogen infrastructure for both transmission, storage and production, including, but not limited to: electrolysers, fuel cells, dispensers. |

## Bibliography

Zhang, Q., Yang, S., Shi, P., Hou, W., Zeng, A., Ma, Y., & Yuan, X. (2020). Economically and thermodynamically efficient heat pump-assisted side-stream pressure-swing distillation arrangement for separating a maximum-boiling azeotrope. *Applied Thermal Engineering*.

Arpagaus, C., Bless, F., Schiffmann, J., & Bertsch, S. (2018). High Temperature Heat Pumps: Market Overview, State of the Art, Research Status, Refrigerants, and Application Potentials.

Cha, S., Lim, J., Kim, Y., Cho, H., Moon, I., & Kim, J. (2022). Development of lactic acid evaporation process model with multi effect evaporator and mechanical vapor recompression system. *Computer Aided Chemical Engineering*.

Dumont, M., Wang, R., Wenzke, D., Blok, K., & Heijungs, R. (2023). The techno-economic integrability of high-temperature heat pumps for decarbonizing process heat in the food and beverages industry. *Resources, Conservation and Recycling*.

Ekezie, F.-G., Sun, D.-W., Han, Z., & Cheng, J.-H. (2016). Microwave-assisted food processing technologies for enhancing product quality and process efficiency: A review of recent developments. *Trends in Food Science & Technology*.

Hamid, K., Sajjad, U., Ahrens, M. U., Ren, S., Ganesan, P., Tolstorebrov, I., . . . Eikevik, T. M. (2023). Potential evaluation of integrated high temperature heat pumps: A review of recent advances. *Applied Thermal Engineering*.

Liu, J., Yang, J., Jia, Y., Wang, Y., Yang, Q., Song, X., . . . Yin, Y. (2023). Techno-economic assessment for black liquor concentration system of chemical pulp integrating mechanical vapor recompression. *Sustainable Energy Technologies and Assessments*.

Madeddu, S., Ueckerdt, F., Pehl, M., Peterseim, J., Lord, M., Kumar, K. A., . . . Luderer, G. (2020). The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat). *Environ*.

Marina, A., Spoelstra, S., Zondag, H., & Wemmers, A. (2021). An estimation of the European industrial heat pump market potential. *Renewable and Sustainable Energy Reviews*.

Obrist, M. D., Kannan, R., McKenna, R., Schmidt, T. J., & Kober, T. (2023). High-temperature heat pumps in climate pathways for selected industry sectors in Switzerland. *Energy Policy*.

Patel, D. N., Matalon, P., & Oluleye, G. (2024). A novel temporal mixed-integer market penetration model for cost-effective uptake of electric boilers in the UK chemical industry. *Journal of Cleaner Production*.

PAWAR, S., & PRATAPE, V. (2015). FUNDAMENTALS OF INFRARED HEATING AND ITS APPLICATION IN DRYING OF FOOD MATERIALS: A REVIEW. *Journal of Food Process Engineering*.

Rastogi, N. (2012). Recent Trends and Developments in Infrared Heating in Food Processing. *Critical Reviews in Food Science and Nutrition*.

Riadh, M., Ahmad, S., Marhaban, M., & Soh, A. (2014). Infrared Heating in Food Drying: An Overview. *Drying Technology: An International Journal*.

Sun, J., Wang, W., & Yue, Q. (2016). Review on Microwave-Matter Interaction Fundamentals and Efficient Microwave-Associated Heating Strategies. *Materials*.

Unterluggauer, J., Sulzgruber, V., Kroiss, C., Riedl, J., Jentsch, R., & Willinger, R. (2023). Design for a Heat Pump with Sink Temperatures of 200°C Using a Radial Compressor. *Energies*.

Variny, M. (2023). Enhancing the Energy Efficiency of a Black Liquor Evaporation Plant by Mechanical Vapor Recompression Integration.

Walmsley, T., Atkins, M., Walmsley, M., & Neale, J. (2016). Appropriate placement of vapour recompression in ultra-low energy industrial milk evaporation systems using Pinch Analysis. *Energy*.

Zuberi, M., Hasanbeigi, A., & Morrow, W. (2022). *Electrification of Boilers in U.S. Manufacturing.*