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Energy
Industries

Sustainable heat solutions
for the pulp and paper sector

A new era
for the paper industry

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List of abbreviations

CAPEX	Capital Expenditure
CHP	Combined Heat and Power
CFCs	Chlorofluorocarbons
CO_2	Carbon Dioxide
COP	Coefficient of Performance
F-Gas	Fluorinated Gas
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
IHX	Intermediate Heat Exchanger
kWh	Kilowatt-hour
MWh	Megawatt-hour
OPEX	Operating Expenditure
PFAS	Per- and Polyfluoroalkyl Substances
SC	Steam Compression
SPHP	Steam Production Heat Pump
Wc	Compressor Work
WHRSG	Waste Heat Recovery Steam Generator

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Synopsis

As the pulp & paper industry advances towards a net-zero-emissions future, it faces significant challenges. With the ndustry's high energy consumption and reliance on carbon-intensive processes, the transition to sustainable energy sources is of paramount importance. High-temperature heat pump technology emerges as a pivotal solution, offering a substantial reduction in CO_2 emissions by converting waste heat into usable process steam. For paper manufacturers, integrating these heat pumps enables more efficient steam generation, reducing dependence on fossil fuels while maintaining production quality. For energy providers, optimizing heat pump design and performance is key to meeting the industry's varying energy requirements cost-effectively.

This paper explores key aspects of implementing heat pump technology, providing insights from studies and economic evaluations conducted in collaboration with industry partners. It highlights the technical potential of heat pumps, focusing on their environmental benefits and commercial viability, with considerations for electricity prices and CO_2 certificate costs. The analysis evaluates energy efficiency, emission reductions, and operational savings, demonstrating how high-temperature heat pumps are becoming a critical component of sustainable pulp & paper production.

Introduction

The pulp & paper industry is the fourth-largest consumer of energy a mong global industries. It accounts for approximately 5% of the total energy consumed by the world's industries and contributes 2% to the direct carbon dioxide (CO_2) emissions from the industry segment. 1 The urgent need to combat climate change has placed significant pressure on industries worldwide to reduce their carbon emissions. Among these, the pulp & paper industry stands out due to its substantial energy consumption and carbon footprint. Decarbonizing this sector is both an environmental imperative and a strategic move towards sustainability and long-term competitiveness. The global demand for and pulp & paper is expected to increase by 2030 and further on.

The global pulp & paper industry is targeting net-zero CO_2 emissions by 2050 at the latest. It is therefore essential to implement measures to reduce the emission intensity of production. This transition will be driven by the following key initiatives:

1. Enhanced efficiency
Enhancing efficiency in pulp and paper production by reducing energy and resource consumption and recovering waste heat,
all while maintaining product quality.

2. Low-carbon fuels
Converting CHP plants and boilers to use biomass or sustainable hydrogen in place of natural gas.

3. Electrification
Replacing fossil fuels with renewable electricity and waste heat recovery for process heating (power-to-heat).

These initiatives are vital to the industry's decarbonization and sustainability goals.

Industrial high-temperature heat pumps will be one important feature to convert low and high temperature process stream directly from the drying sections to useful high quality process heat. This approach offers the dual benefit of reducing reliance on fossil fuels when combined electrification with renewables as an energy source and enhancing the overall efficiency and economic profitability of the paper drying process.

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Energy supply in pulp & paper production

Energy demand in this sector varies depending on the type of pulp produced, the grade of paper manufactured, and whether the facility operates as an integrated mill or a standalone production site. Efficient energy use is essential to minimize costs and lower the industry's environmental footprint. In the pulp & paper industry, there are a number of key processes that require high amounts of energy.

Pulping process

This includes both mechanical and chemical methods, each with varying energy demands.

Mechanical pulping
Mechanical pulping is notably energy-intensive, relying heavily on electricity for the mechanical grinding of wood fibers, consuming around 1,500 to 3,500 kWh per ton of pulp.

Chemical pulping
Chemical pulping involves the use of chemicals and heat, requiring less electricity but significant thermal energy, typically around 500 to 1,200 kWh per ton of pulp.

Papermaking process

After pulping, the paper production process involves:

Water removal
Pressing and drying the paper web are energy-intensive, especially the drying phase, which involves evaporating large amounts of water.

Drying phase
This is the most energy-demanding part, requiring both steam and electricity, and can consume between 2,000 and 3,000 kWh per ton of paper, depending on the paper grade. The drying section is a critical stage in the production of pulp & paper. Its purpose is to reduce the moisture content of the paper, which still retains a significant amount of moisture from the preceding processes. The drying section ensures that the paper achieves the desired strength and surface quality.

Other processes

Ancillary systems such as air handling, wastewater treatment, and chemical recovery also contribute to the overall energy consumption in the production process.

In total, the specific energy consumption in integrated pulp & paper mills ranges between 7–9 MWh per ton of paper, depending on the type of paper being produced, the energy efficiency of the mill, and the quality of the raw material.

To meet these high energy demands, pulp & paper mills use various sources of energy. These sources can be categorized into renewable and non-renewable energy, with a growing focus on shifting towards more sustainable energy solutions.

Fossil fuels

Fossil fuels such as coal, natural gas, and oil have traditionally been the primary sources of energy for many industries, including pulp and paper.

Natural gas
Widely used for generating steam and heat in boilers and for drying paper. It is often favored due to its lower emissions compared to coal or oil and its ease of availability in many regions.

Coal
Some older pulp & paper mills still rely on coal-fired boilers to generate steam and electricity. However, due to its high carbon emissions and environmental concerns, coal use is declining.

Oil
In regions where natural gas or biomass are less available, oil may be used as a fuel source, though it is generally more expensive and carbon-intensive.

Biomass

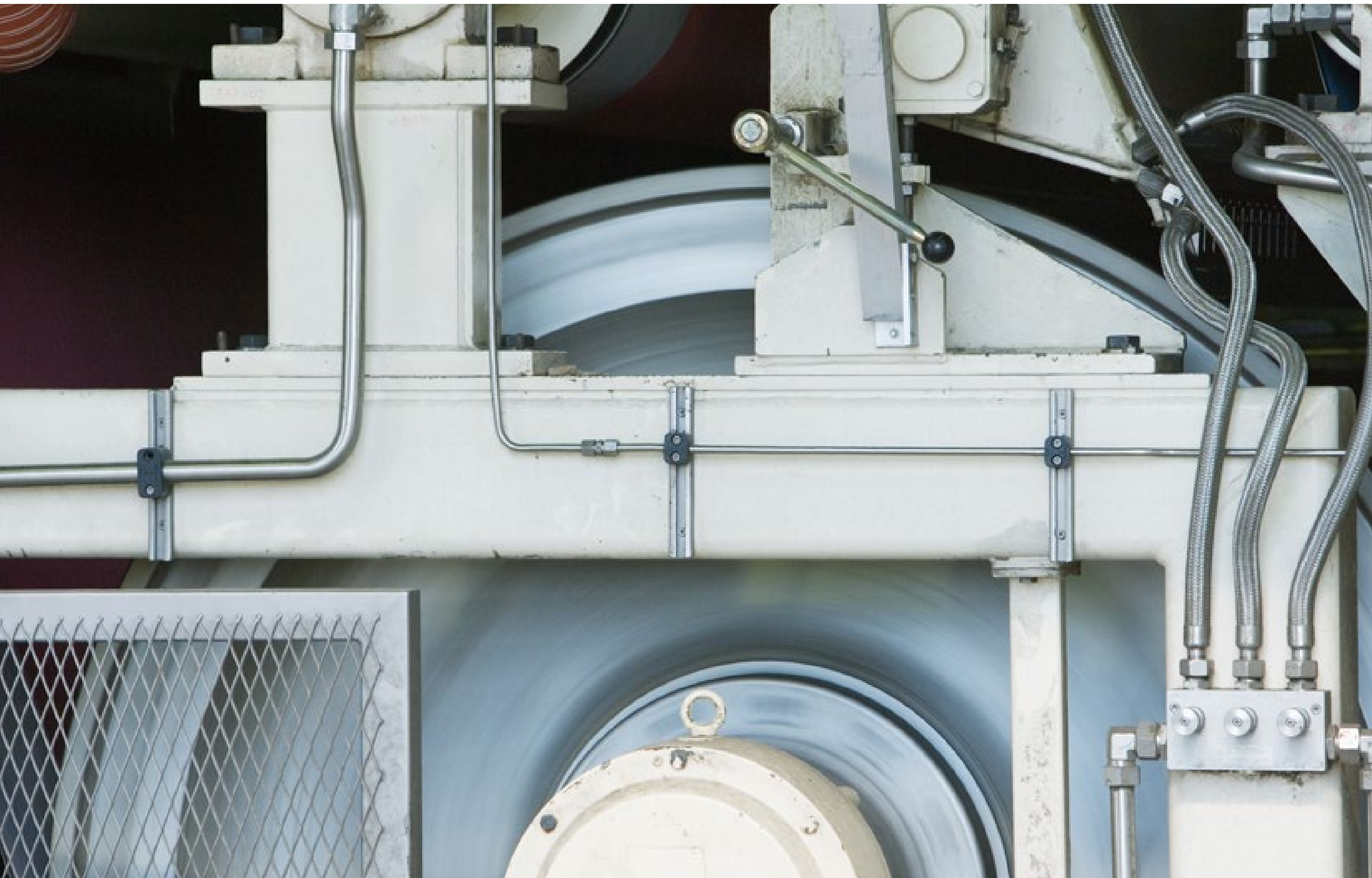
Biomass has become a key energy source in the pulp & paper industry, especially in integrated mills, due to the availability of biomass by-products from the pulping process itself.

Black liquor
In kraft chemical pulping, a significant by-product called black liquor is generated. This substance contains lignin and other organic materials, which can be burned to produce steam and electricity.

By utilizing black liquor as a fuel, integrated mills can meet a substantial portion of their energy needs from this renewable source, making chemical pulp mills some of the most energy-efficient in the industry.

Wood residues
Many mills also burn wood waste, bark, and other residues to generate steam and electricity. This reduces reliance on external energy sources and lowers the carbon footprint of the mill.

Biomass energy typically provides 50-70% of the energy requirements in kraft pulp mills, contributing to their overall sustainability.



Cogeneration

Cogeneration (Combined Heat and Power - CHP) is widely implemented in pulp & paper mills to improve the overall energy efficiency. CHP systems produce both electricity and heat from the same fuel source, recovering heat that would otherwise be “lost” in power generation.

Steam turbines
The steam generated in boilers is used to produce electricity through steam turbine generator sets. In paper production, steam is extracted from the turbine at specific enthalpy levels required for heating and drying. Here, the steam turbine acts as a pressure reduction station, supplying process steam while simultaneously generating electricity.

Gas turbines
Gas turbines integrate into various processes, including power generation and heat supply, boosting overall operational efficiency. In a combined heat and power (CHP) configuration, gas turbines simultaneously generate electricity while harnessing exhaust heat for process heating or drying applications. For instance, they can deliver hot gases directly to a Yankee hood used in tissue production or channel the exhaust through a waste heat recovery steam generator (WHRSG) for further energy optimization.

Cogeneration systems can achieve energy efficiencies of 70-80%, significantly higher than conventional power generation systems. In pulp mills, this approach often integrates well with biomass energy sources, creating a highly efficient and sustainable energy loop.

Electricity from the grid

While many mills generate a significant portion of their energy internally, some still rely on grid electricity for their operations, especially mechanical pulping mills, where electrical energy plays a dominant role in breaking down wood into fibers. Depending on the local grid, this electricity may come from a mix of sources, including renewables (wind, solar, hydro) or fossil fuels.

In countries or regions with a high share of renewable energy, mills using grid electricity can reduce their overall carbon footprint.

Renewable energy

Hydropower

In regions with abundant water resources, pulp & paper mills frequently use hydroelectric power as part of their electricity supply. This is particularly common in countries like Sweden, Norway, and Canada.

Solar energy

Though not widely used for direct production processes, some mills use solar panels to generate electricity for auxiliary operations such as lighting and administrative buildings.

Wind energy

Similar to solar, wind energy supplements grid electricity in some facilities, reducing reliance on non-renewable sources.

Figure 1 highlights CO_2-neutral energy sources and technologies for generating process heat in the pulp & paper industry.

Heat pumps will play an increasingly important role in the future, driving the electrification of heat generation and expanding their contribution to decarbonization, particularly in the pulp & paper industry.

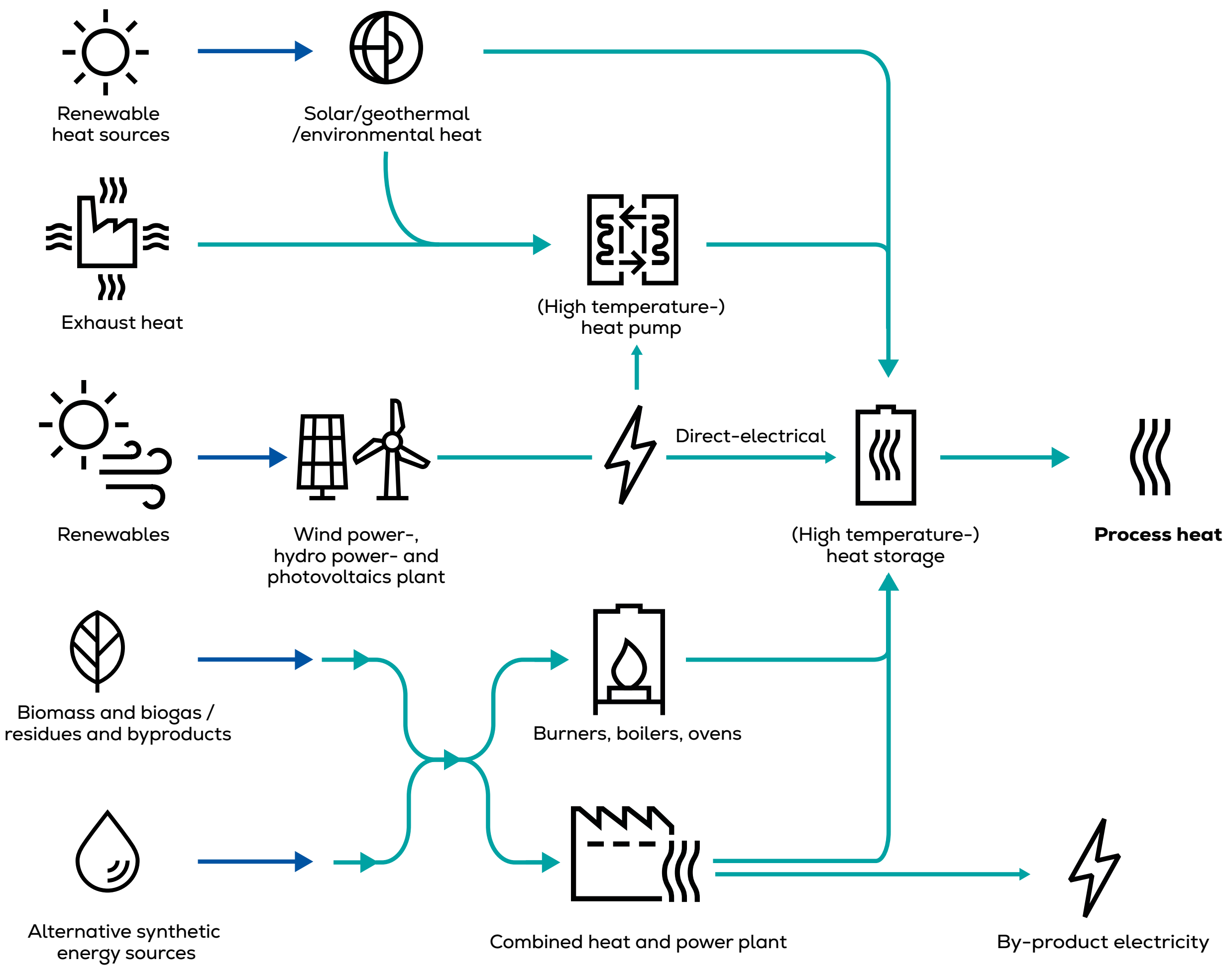


Figure 1: Decarbonized process steam production, technologies and energy sources 2* adapted

Steam production with high-temperature heat pumps

Heat pump solutions efficiently convert ambient or waste heat into usable energy. They offer a key advantage over electrical boilers by generating more heat than the electrical energy required to run them.

Process steam can be generated in three ways:

- Heat pump only (Steam production heat pump, SPHP)
- Steam compression only (Steam compression, SC)
- A combination of both (SPHP+SC)

The efficiency of the heat pump system is determined by the Coefficient of Performance (COP) which is the ratio of the rejected heat and compressor work, and is dependent on both temperature lift and cycle efficiency.

In general, the COP calculation is simple: It is the difference of thermal power at the sink output and the sink input over the compressor work.

$$COP = \frac{\Delta Q_{sink}}{W_c}$$

A steam compressor, with appropriate interstage cooling to optimize its compression efficiency, typically has a coefficient of performance slightly below 1.

However, when combining a heat pump with a steam compressor (SPHP+SC), the COP is defined as:

$$COP = \frac{\Delta Q_{sink}}{W_c(SPHP) + W_c(SC)}$$

where ΔQsink represents the difference in thermal power between the steam compressor discharge and the heat pump sink inlet (usually the feed water). Such a combination typically yields a COP ranging from just under 2 to over 3 depending of the refrigerant used and the cycle configuration.

Figure 2 illustrates the standard principle of a heat pump used for steam production, which is then supplied to a process steam header. The SPHP system operates on a typical closed-loop heat pump cycle designed to generate steam at low pressure levels. This system comprises an evaporator at the heat source, a compressor, a condenser at the heat sink to heat and evaporate the feed water, and a throttle valve to complete the heat pump cycle. Depending on the refrigerant and the configuration of the heat pump cycle, this system can produce steam at low pressure levels, such as up to 2 bara.

A steam compressor (SC) is placed on the heat pump's steam side to supply steam to the process header. It can either be integrated with the heat pump or installed as a standalone unit.

To optimize efficiency, the steam pressure between the heat pump and the steam compressor is adjusted to achieve the highest overall coefficient of performance (COP) for the system. Lower intermediate pressure results in higher efficiency but requires a larger steam compression component. Additionally, actively cooling the steam during compression with injection water enhances overall efficiency and reduces the size of the heat pump.
The types of compressors typ-

ically used for industrial heat pumps include scroll, reciprocating, screw, and both inline and radially geared centrifugal compressors. However, centrifugal compressors are exclusively used for large-scale industrial applications exceeding 10 MWth. A typical radially geared centrifugal compressor is shown in figure 3.

They have a strong track record within the chemical and petrochemical industries and are designed in accordance with widely recognized industrial standards.
In general, various refrigerants can be used for large heat pump cycles. The thermodynamic properties of the refrigerant and therefore the choice of the working fluid highly influences the heat pump process and can be used for process optimization.

Thus it is important to consider various categories of properties:

- Thermodynamic properties such as critical temperature and pressure, and evaporation/condensation enthalpy
- Chemical properties. Compatibility with component materials such as metals, seals, and chemical stability
- Environmental factors such as potential for greenhouse warming, ozone depletion, and degradation products
- Safety considerations such as flammability, toxicity, detectability, and others
- Commercial factors including cost (CAPEX and OPEX), and supplier market availability

Refrigerants can be categorized as natural or synthetic. Natural refrigerants include of hydrocarbons such as butane, propane, as well as ammonia and carbon dioxide. Synthetic refrigerants like Hydrofluorocarbons (HFCs) are designed for specific applications. They have replaced Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs), which harm the ozone layer. The future of synthetic refrigerants is currently uncertain due to regulations such as the F-Gas Regulation and REACH (which governs per- and polyfluorinated substances, PFAS). As a result, natural refrigerants are considered more suitable for future use.

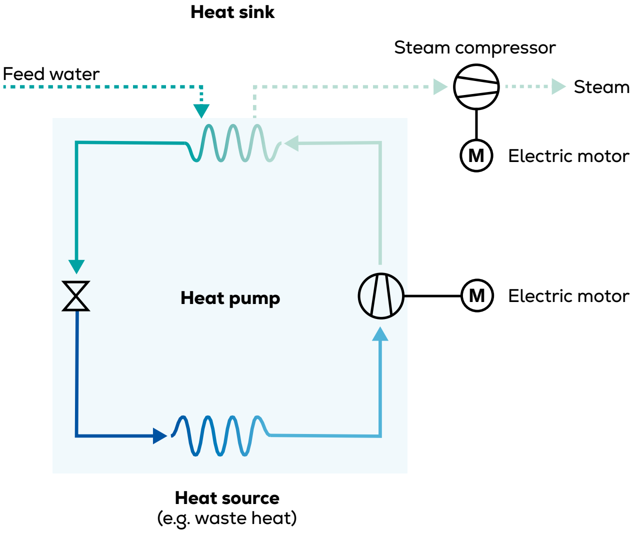


Figure 2: Steam production with heat pump SPHP and additional steam compression SC

Figure 3: Integrally geared compressor

Steam supply for the paper production process using heat pumps

Steam is essential in the paper production process, from pulping to drying. Efficient steam management improves production quality while boosting energy efficiency and sustainability.

Traditionally, steam provides heat for the drying process in the paper industry. It is generated using boilers or gas turbine CHP (Combined Heat and Power) plants powered by fossil or renewable fuels. These methods produce high- or medium-pressure steam, with medium-pressure steam supplied directly to the drying sections. Medium-pressure steam can be directly supplied to the drying sections. High-pressure steam is used in steam turbines for CHP generation. These turbines regulate and distribute steam to the appropriate medium and low-pressure steam headers, ensuring the correct amount and conditions of steam delivered to the drying sections of the paper machine. This process involves reducing high-pressure steam through turbines or throttling valves to meet the paper drying requirements. The steam is adjusted to the appropriate pressure and temperature to ensure optimal conditions for the drying process.

Currently, waste heat from humid saturated air in the paper drying process is used to heat plant buildings or support other low-temperature thermal processes. Traditionally, steam provides heat for the drying process in the paper industry. It is generated using boilers or gas turbine CHP (Combined Heat and Power) plants powered by fossil or renewable fuels. These methods produce high- or medium-pressure steam, with medium-pressure steam supplied directly to the drying sections. To optimize the use of these heat pumps, the paper manufacturer, the paper machine supplier, and the heat pump manufacturer must develop a joint energy concept. The approach differs significantly between greenfield installations and brownfield projects. In brownfield projects, existing steam production systems and headers must be considered, requiring a customized solution for each paper mill.

The goal, however, remains the same: Combining waste heat streams from the paper production process to design an optimized heat pump cycle. The heat pump's efficiency (COP) largely depends on the temperature difference between the heat source and sink. Minimizing this difference is crucial for achieving maximum efficiency.

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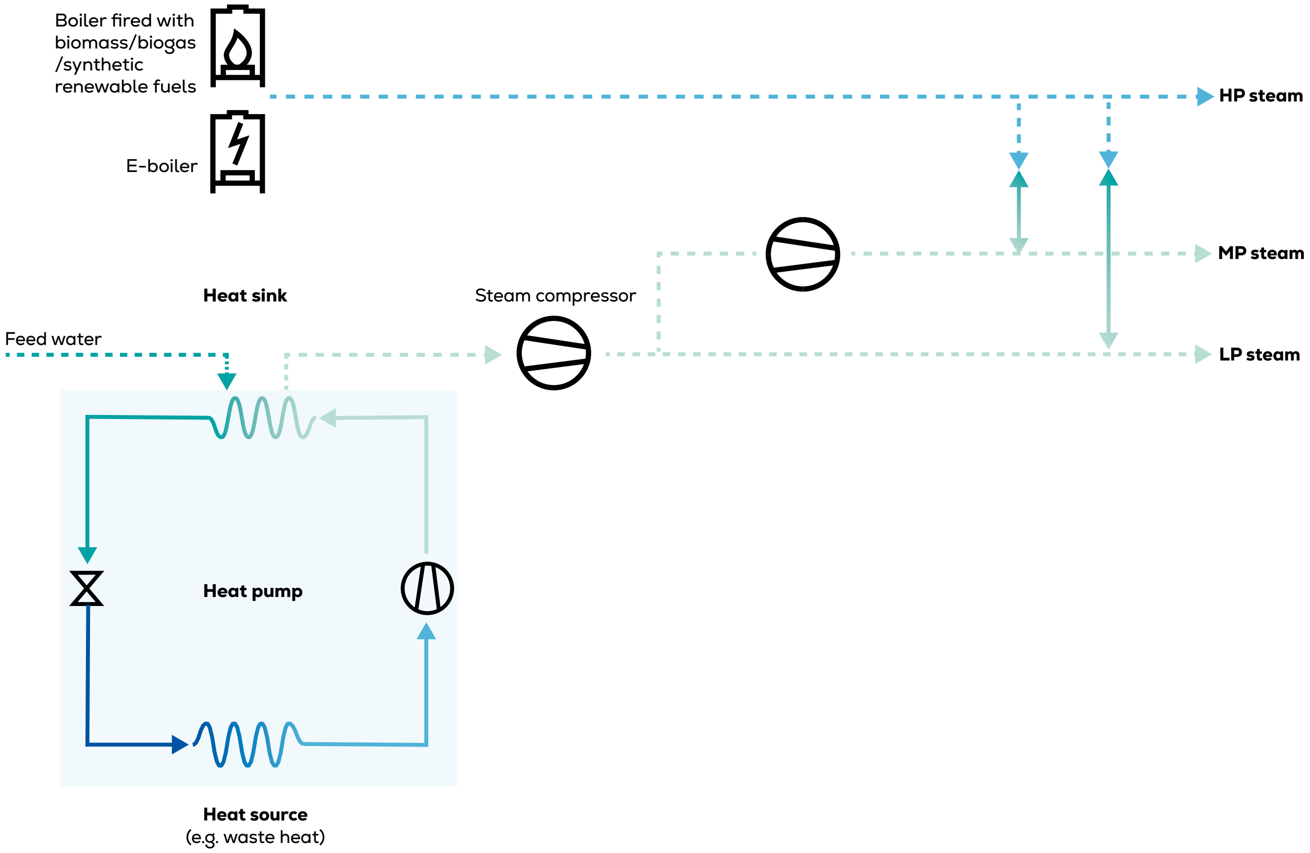

Figure 4: Process schemata for steam supply with heat pumps

Taking a closer look at an optimized high-temperature heat pump, it becomes clear that it can only produce low-pressure steam. To achieve the required steam parameters in a paper mill, additional steam compressors are necessary. To optimize the system, cascading the heat pump and steam compressors from low to higher steam conditions is recommended. This method contrasts with traditional steam generation, which reduces high steam conditions to lower levels.

Heat pumps are most cost-effective when designed for base load operation, where maximum efficiency is achieved. But nevertheless the operating range of a heat pump driven by turbo compressors extends down to a partial load of 30%, although with slight reductions in efficiency.

When planning an energy concept, it is crucial to ensure a wide control range for steam production across all operating conditions (e.g., start-up, part load, full load). Using a single heat pump for all load scenarios is not recommended. Instead, cascaded heat pumps and steam compressors, electric boilers, and thermal storage may be applicable, depending on the specific requirements of the individual paper mill. This also provides a solution for the startup phase of the paper machine when no waste heat is available. A typical process diagram is shown in **figure 4**.

Figure 5 shows a typical layout of a heat pump system with a radial integrally geared com-

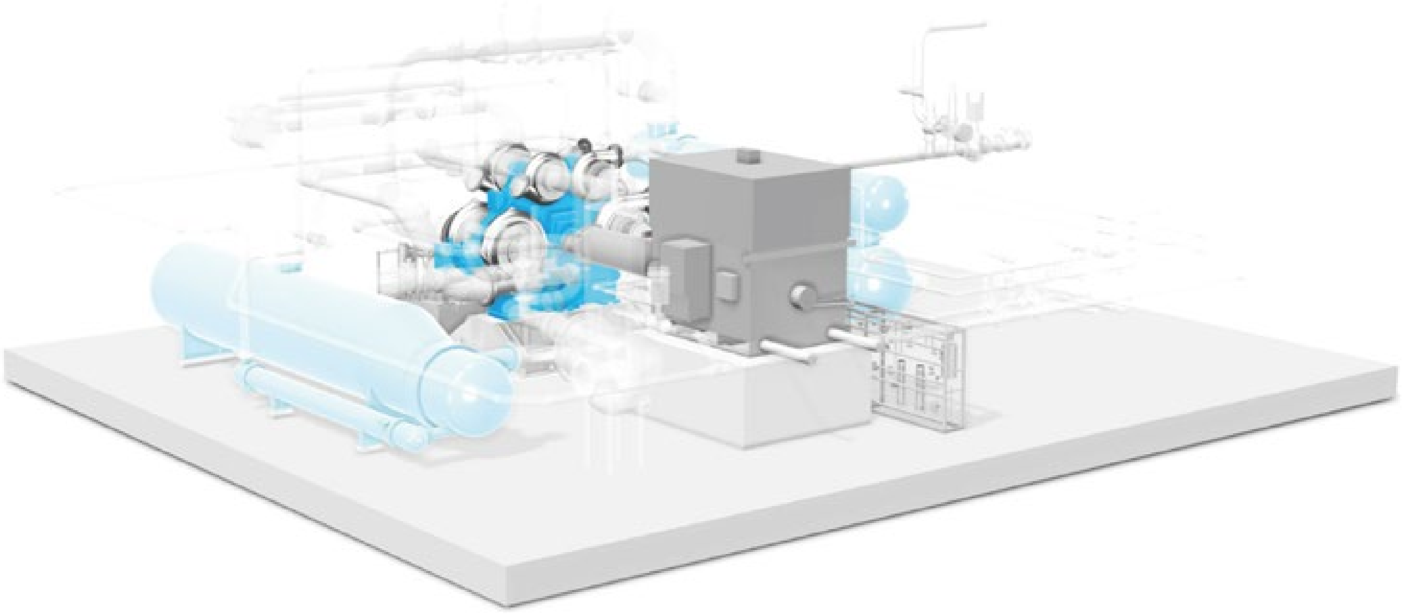

Figure 5: Typical heat pump system arrangement

pressor. Here, all radial compressor stages (heat pump and steam compressor stages) are combined into a single package, eliminating the need for separate steam compressors and reducing space and investment costs.

This multiple heat pump system, includes:

A compressor system mounted on a base frame, synchronous motor with starting frequency converter, lube oil unit.

- Process equipment, such as a condenser, subcooler, evaporator, superheater, and flash box
- An internal piping package, consisting of: piping of the complete HP loop, process valves and instruments, interconnecting cables and auxiliary piping.
- A control system with connections to the overall plant control and operating system
- The following case study will present an economic comparison between fossil steam generation in a gas-fired boiler and steam generation with a high-temperature heat pump.

Case study: Evaluating the technical and economic benefits of heat pump solutions

A technical and economical evaluation of heat pump solutions for steam generation was conducted. An optimized heat pump solution is designed to meet the typical steam demand of a paper factory.

This example assumes constant steam demand of 41 t/h at 5 bar and 170°C throughout the year, which applies to most paper industries. The heat source for the heat pump is humid air, available from the paper process at ambient pressure. The specifications of the humid air are detailed in Table 1. The boundary conditions for the technical and economic calculations are outlined in Tables 1 and 2.

Electricity prices vary by location and future market trends, influencing the economic viability of the heat pump solution. This evaluation considers different industrial electricity prices. Currently, the electricity price in Germany is 248 €/MWh for industries and businesses. The electricity price range evaluated spans from 200 €/MWh to 300 €/MWh, offering insights into how price variations affect the viability of the heat pump solution. The study uses the German natural gas price for industries and businesses, set at 97 €/MWh. This price applies to the conventional steam generation solution and influences the evaluation of the heat pump's net benefits. The natural gas price is kept constant for the study. The service costs of the heat pump system are included in the economic evaluation, while subsidies are excluded.

Table 1: Technical boundary conditions of the combined heat and power evaluation

Parameters	Data
Steam demand [t/h]	41.0
Steam pressure [bara]	5
Steam temperature [°C]	170
Feed water temperature inlet condenser heat pump [°C]	102
Condensate return fraction [%]	100
Condensate return temperature [°C]	95
Humid air temperature source 1 [°C]	85
Humid air mass flow source 1 [t/h]	120.6
Humid air temperature source 2 [°C]	75
Humid air mass flow source 2 [t/h]	193.32
Average CO_2 emissions from electrical power grid by conventional power plants [g/kWhe]	450
Share of electrical power generated by renewable sources [%]	45
Average yearly CO_2 emissions for a car [g/km]	120
Average yearly distance for a car [km]	12.000

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Table 2: Economic boundary conditions

Parameters	Data
Electricity prices bought from the grid [€/MWh]	200, 248, 300
Natural gas price [€/MWh], (Germany)	97
CO_2 certificate cost [€/ton], (Germany, Sweden, Finland, etc. – based on the latest updates on 2024)	90, 115, 127, 150
Interest rate [%]	8
Conventional boiler efficiency [%]	90
Yearly operating time [hours]	8.500

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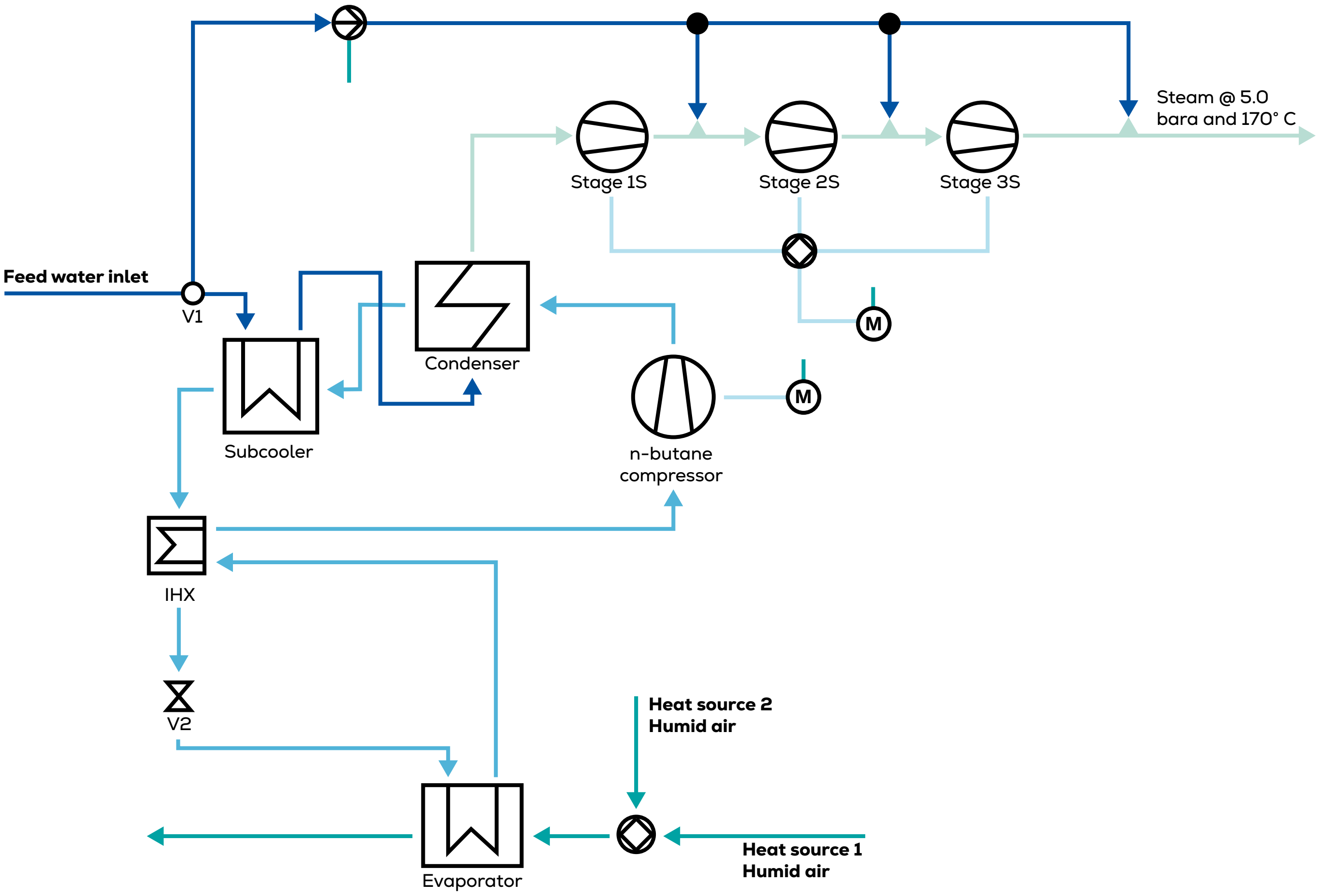

Figure 6: Heat pump solution for steam production purposes

Description of heat pump cycle for steam generation

The heat pump cycle for steam generation consists of several components (**Figure 6**), including a compressor that moves the refrigerant through the refrigeration cycle. This cycle extracts and processes heat in multiple stages. It includes several heat exchangers: a condenser, a subcooler, an intermediate heat exchanger, and an evaporator.

The refrigerant used in this cycle is n-butane, and the heat pump cycle operates on the reverse Rankine principle. In the first step, the heat pump generates steam at 1.09 bara, which is then compressed in the second step to 5 bara and 170°C. The T-S diagram (**Figure 7**) illustrates the various stages of the cycle.

Basically the cycle operates as follows:

1. Polytropic compression of the refrigerant (n-butane): The refrigerant is compressed from a low pressure and temperature (5.18 bara, 95.4°C) to a high pressure and temperature (19.2 bara, 145°C) to supply the heat required by the condenser.

2. The compressed refrigerant at high pressure drives the condenser to produce steam. During this step, the refrigerant condenses at nearly constant pressure (with minor losses accounted for during condensation). This process produces 6.93 t/h of saturated steam at 1.09 bara, based on the total feed water available at the condenser inlet.

3. The condensed refrigerant is used in the subcooler to preheat the condensate return flow from 95°C to 102°C. This preheated condensate serves as feed water for the condenser during steam generation.

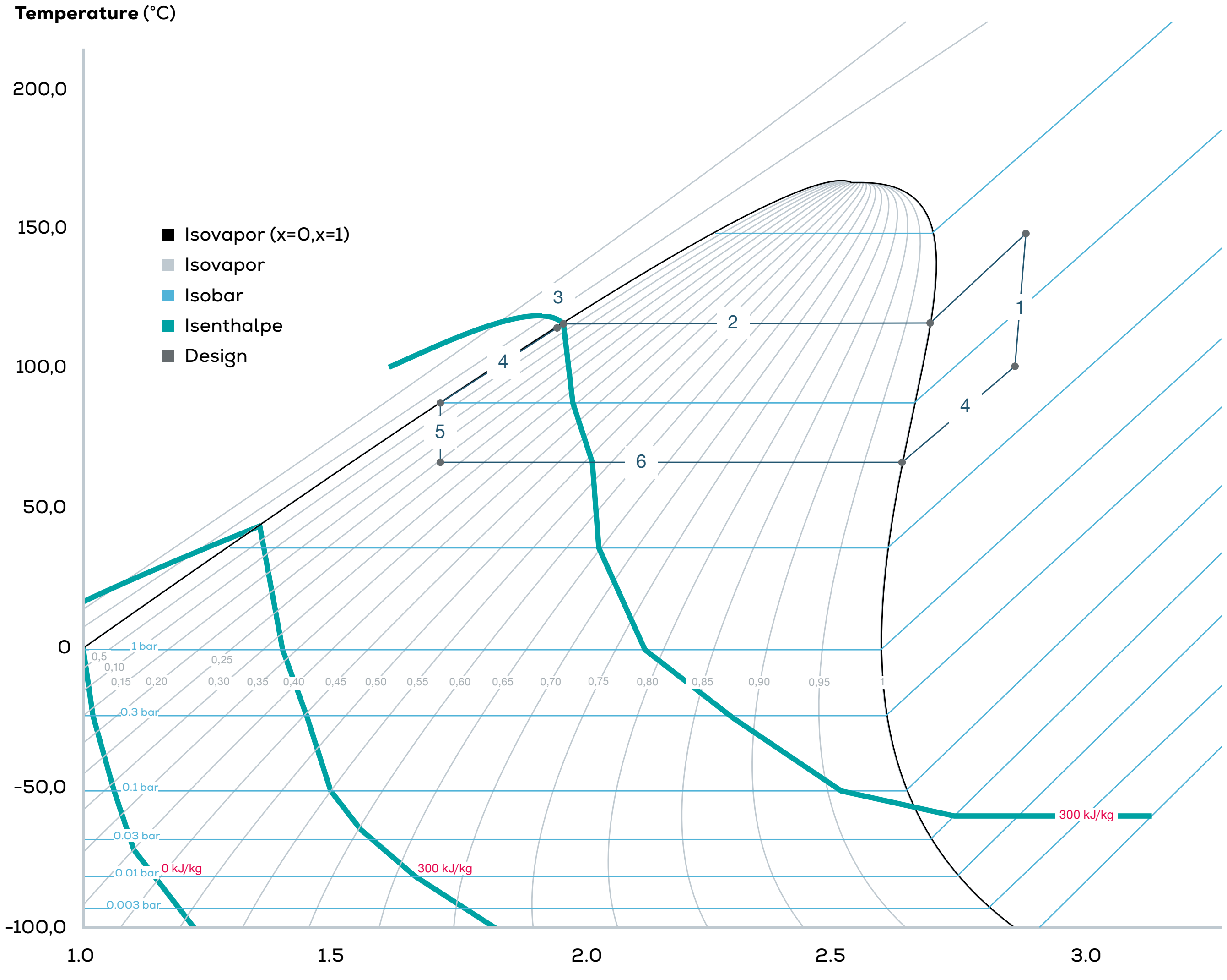

Figure 7: T-S diagram of the reverse rankine cycle with n-butane

4. The liquid n-butane exiting the subcooler powers the intermediate heat exchanger (IHX) to preheat the saturated n-butane from the evaporator.

5. During the expansion phase, the refrigerant pressure drops to a lower level, resulting in a two-phase mixture of liquid and gas. The gas fraction, approximately 21%, is significantly lower than the liquid fraction.

6. Evaporation: During this step the heat source available (humid air) is used to evaporate the n-butane available after the expansion process.

Under ideal conditions, the pressure of the refrigerant remains constant. However, in real operating conditions, minor pressure losses occur during the evaporation process on both the hot and cold sides.

After the evaporation process, the saturated n-butane is preheated by the IHX, as described in Step 4. The preheated n-butane is then used by the compressor, restarting the cycle at Step 1 (polytropic compression). Regarding the steam process, the saturated steam exiting the condenser is compressed to 5 bara and 170°C. Between steam compressor stages, a controlled amount of feed water is injected to regulate the compression process. The final steam output from the steam compressor is 41 t/h.

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72%

less CO_2 emissions than the conventional configuration

Basic performances of the heat pump solution

The key performance metrics of the heat pump solution are summarized in Table 3. The results indicate that the COP of the heat pump, with or without steam compression, is at a high level. This is attributed to the optimized cycle design and the practical feasibility of the equipment.

Reduction of CO_2 footprint

The CO_2 footprint reduction of the heat pump solution was evaluated using the boundary conditions outlined in Tables 1 and 2. The CO_2 emissions were calculated based on the total electrical power consumption of the heat pump plant, accounting for the share of renewable energy from the public grid (Table 2). In comparison, the conventional steam generation solution relies on a gas-fired boiler. The difference in CO_2 emissions between the two approaches represents the reduction achieved by the heat pump solution.

According to Table 4, the heat pump solution reduces the CO_2 footprint by 41,200 tons per year, achieving nearly 72% lower emissions compared to the conventional configuration. To put this in perspective, the standard CO_2 emissions for a car are 120 g/km (Table 1). Based on an average mileage of 12,000 km per year, the CO_2 reduction achieved by the heat pump solution is equivalent to taking 28,610 cars off the road.

The results confirm that the heat pump solution is highly efficient and environmentally friendly. This is primarily due to its high COP (2.91) and the significant share (45%) of renewable energy in the public grid, as outlined in Table 1.

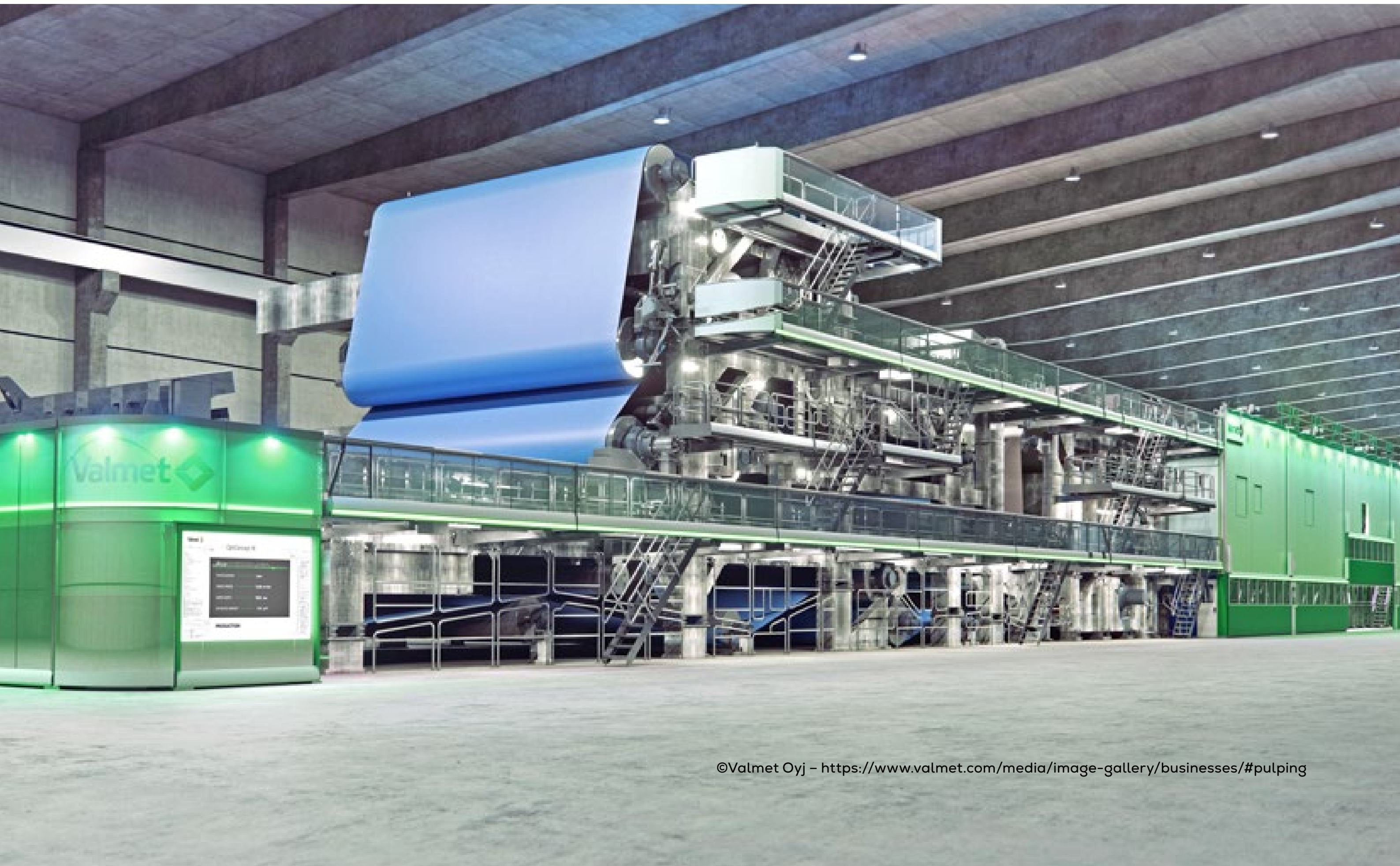
Table 3: Performances of the heat pump solution for steam generation at 5 bara and 170°C required for the paper industry

Parameters	Data
Steam production at 1.09 bara outlet condenser [t/h]	36.93
Steam thermal power at 1.09 bara without steam compressor [MW]	23.4
Steam production at 5 bara and 170°C outlet steam compressor [t/h]	41.0
Total steam thermal power at 5 bara and 170° generated by the heat pump solution [MW]	27.74
Electrical consumption heat pump without steam compressor [MW]	5.52
Electrical consumption heat pump solution including steam compressor [MW]	9.54
COP heat pump without steam compression	4.24
COP heat pump including steam compression	2.91

Table 4: Reduction of CO_2 footprint results*

Parameters	Data
Yearly CO_2 emissions of heat pump solution [tons/year]	16.420
Yearly emissions of gas fired boiler [tons/year]	57.620
Reduction of the CO_2 footprint by the heat pump solution [tons/year]	41.200

* The CO_2 emissions of the heat pump solution are based on the electrical power consumption that is supplied by the grid. 45% of this electricity is generated from renewable sources, significantly contributing to the reduction in CO_2 emissions associated with the heat pump's operation.



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Economic evaluation of combined heat and power solutions

The purpose of this economic evaluation is to quantify the benefits of the studied heat pump solution. In the paper industry, the most common conventional configuration is a gas-fired boiler, which serves as the cost reference.

The annual operating costs of the heat pump solution include electrical power consumption and maintenance.

In comparison, the annual operating costs of a conventional gas-fired boiler include natural gas expenses, CO_2 certificate costs, and maintenance.

The difference in operating costs between the heat pump solution and the conventional boiler represents the annual net savings (benefits) of the heat pump system. The cumulative annual savings over a complete life time of thirty to forty years represents the net cash flow. The typical period under review for the heat pump solution is ten years. The net cash flow corresponding to this period, represents the net present value. The dynamic payback time depends on the interest rate, annual savings, and total investment in the heat pump solution.

The heat pump solution investment includes capital expenditures for equipment such as compressors, heat exchangers, and piping, as well as costs for installation, commissioning, and civil construction.

Figure 8 illustrates the net cash flow generated by the heat pump solution over a 10-year period, considering varying electricity prices and the current natural gas price in Germany. The CO_2 certificate cost is fixed at 90 €/ton. Higher electricity prices lead to longer payback times and lower net present values after 10 years.

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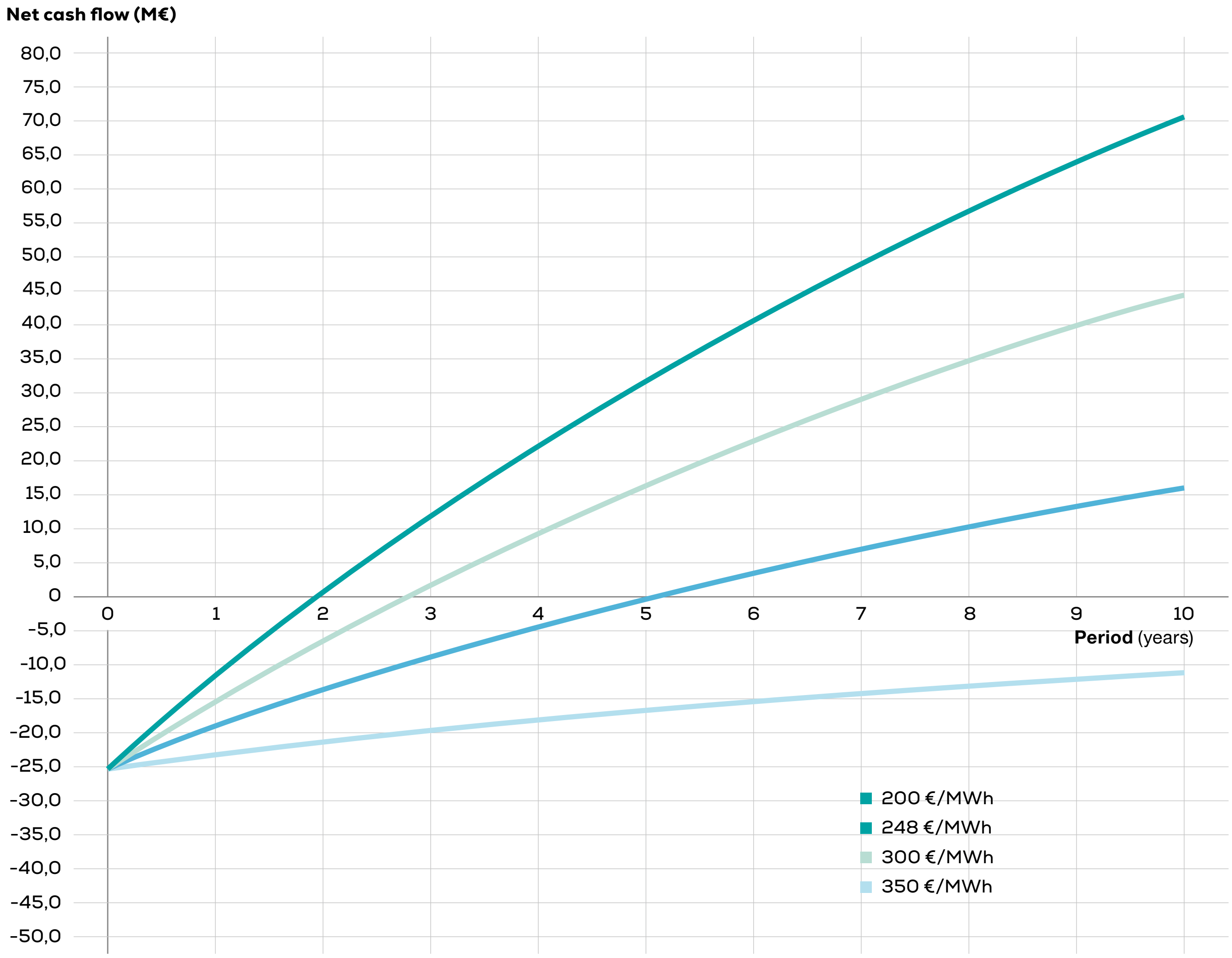

Figure 8: Influence of electricity price the evolution of the net cash flow over a 10-year period

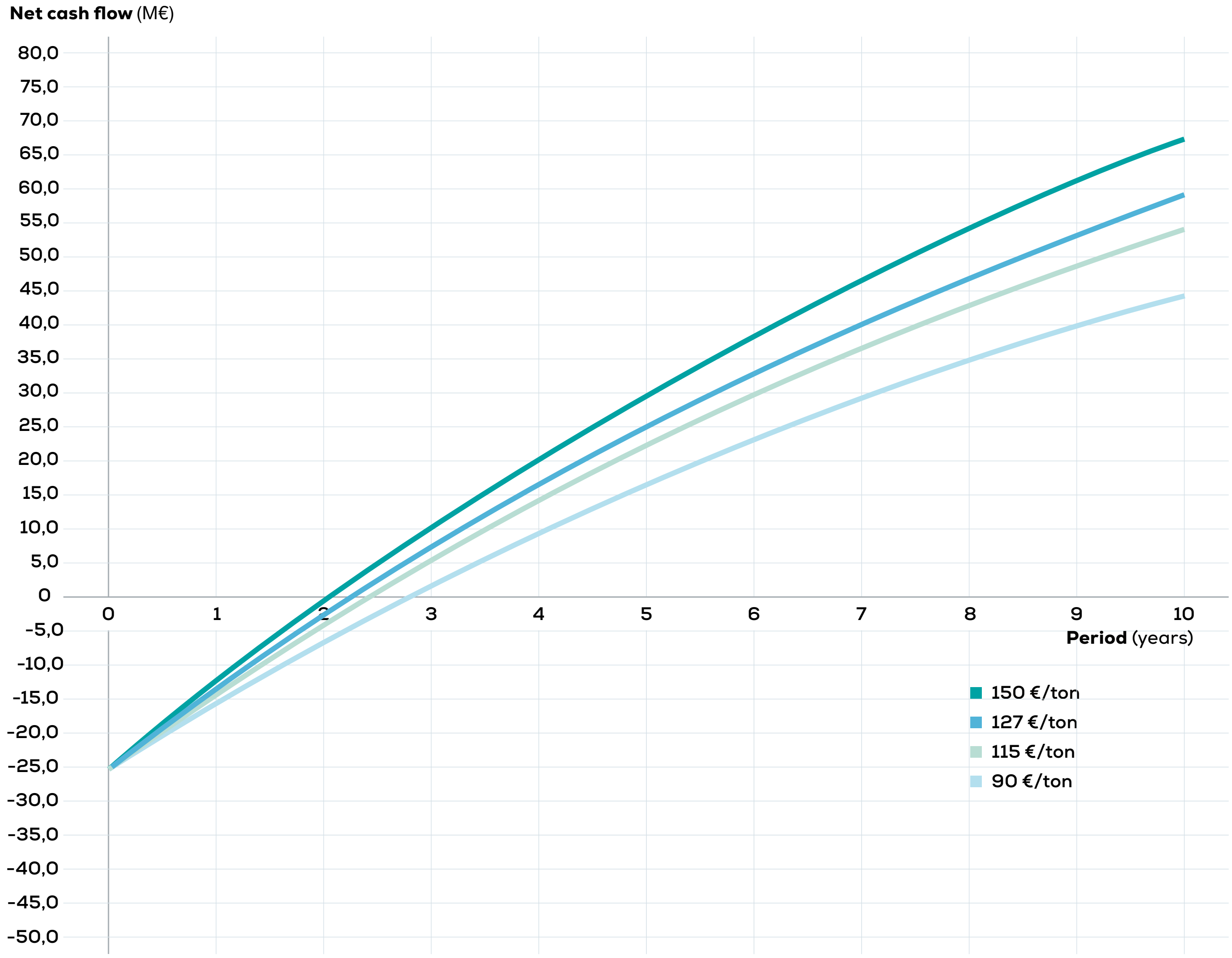

Figure 9: Impact of CO_2 certificate cost on the net cash flow over a 10-year period

The net present value after 10 years decreases as electricity prices rise. For electricity prices increasing from 200 to 300 €/MWh, the electricity-to-gas price ratio shifts from 2.1 to 3.1. In this scenario, the payback time remains below 5 years, and the net present value ranges from 16.2 M€ to 70.6 M€. This indicates that the heat pump solution is highly attractive and viable.

Figure 9 illustrates the net cash flow generated by the heat pump solution over a 10-year period for various CO_2 certificate costs.

This evaluation considers energy prices in Germany, with an electricity price of 248 €/MWh and a natural gas price of 97 €/MWh. From **Figure 9**, it is evident that higher CO_2 certificate costs lead to shorter payback times and higher net present values over the 10-year period.

Summary of the technical and economic study

The heat pump solution evaluated for steam generation is representative of typical applications in the paper industry.

The main technical and economic take-away points are:
1. The heat pump system features a high and efficient Coefficient of Performance (COP), ensuring low electrical power consumption.

2. The significant reduction in CO_2 emissions highlights the environmental benefits and cleanliness of the heat pump solution.

3. Economically, the heat pump solution is highly attractive due to its high net present value and short payback period (less than 5 years) for electricity prices below 300 €/MWh and CO_2 certificate costs of 90 €/ton or higher. However, the profitability is reduced in cases where electricity prices are significantly higher compared to natural gas prices.

In general, the benefits of the heat pump solution could increase if subsidies are included in the economic calculations. However, conducting a comprehensive feasibility study requires a detailed annual profile of the steam process.

Reduction of th CO_2 footprint

41.200

tons/year

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Outlook and conclusions

High-temperature heat pumps represent a transformative solution for the pulp & paper industry, addressing the critical need for energy-efficient, CO_2-reducing technologies by converting waste heat into process steam. By balancing energy demands with sustainability goals, heat pumps enable substantial reductions in carbon emissions and fossil fuel dependency, supporting global decarbonization efforts. As highlighted in this study, this technology is central to Everllence' mission to deliver sustainable, high-efficiency solutions for the industrial sector, addressing the diverse requirements of both greenfield and brownfield projects.

The economic case for heat pump technology is compelling, with short payback periods and significant long-term savings driven by CO_2 emissions reduction and renewable-powered electrification. Future advancements in compressor and refrigerant technologies will be informed by practical field insights and collaborative industry research.

As the pulp & paper industry continues its path toward net-zero emissions, heat pumps will remain essential, supported by Everllence' commitment to technological innovation and robust environmental strategies.

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Figures

Tables

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MAN Energy Solutions SE has been renamed to Everllence SE and its products are being rebranded from “MAN” and/or “MAN Energy Solutions” to “Everllence”. As this is an ongoing process, any reference to “MAN” and/or “MAN Energy Solutions” is actually a reference to “Everllence”.