Energy supply for pulp and paper production

MAN Energy Solutions
Future in the making

Reliable, affordable and sustainable energy supply for the paper industry

Synopsis

The technology involved in the production of pulp and paper is very challenging. But what about its energy supply? Due to the large amount of energy required in the production process, the energy supply deserves to be given appropriate attention.

This paper will outline the types of energy needed for the production process and explain which primary energy sources can be used. And it will focus on suitable energy conversion technology, its availability and the benefits of its service concepts. We will also address the reduction of lifecycle costs and discuss sustainable solutions to satisfy all stakeholders.

Operators of pulp and paper production facilities need to translate the considerations addressed into a specific concept to ensure a reliable energy supply. To help them with their decisions, we conclude this paper with a case study that demonstrates an efficient solution for a medium sized paper production facility. In this case study, we show how the facility's energy supply can benefit from a combined heat and power solution using a specific gas turbine. The technical, economic and ecological evaluations will be presented in detail.

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Use of energy in the production process

Pulp and paper production requires a large amount of energy. Therefore, a reliable and cost-effective supply of energy is important for continuous, profitable and environmentally friendly production. Each product requires an individual set of production steps, each with its own energy demand, hence suitable energy systems can differ between production sites.

Unless paper production relies entirely on secondary fibers as feedstock, it will require the production of primary fibers. This process is known as pulping. Chemical pulping, the dominant pulping method, needs thermal as well as electrical energy. Mechanical pulping, which makes up most of the remaining share of the pulping market, requires a significant amount of electricity to power electric motors for grinders or refiners. If a subsequent thermal treatment is used, a heat source is integrated into the production process. Pulping will often be separated from the subsequent paper production; in this case the intermediate products need drying before transport.

The process steps for non-integrated paper production require an energy supply system that differs from that required for pulping. Paper production requires a significant amount of thermal energy to increase the dry matter content to approximately 95%. This is common regardless of the production process and is in addition to the electric energy used for mechanical drives, for example for grinders, vacuum blowers or cylinders. Thermal drying of paper in the drying section typically relies on saturated steam transferring heat to a large number of cylinders by condensation. Operators select the steam pressures of cylinder groups, usually between 3 and 20 bar, depending on the desired product properties. Tissue production and some paper production processes may employ additional drying methods. In tissue production, impingement drying with hot gas at temperatures of up to 750 °C is a common additional process step. In some regions, it is replaced by through air drying, using hot gas at temperature levels below 300 °C. Drying the coating of paper, infrared drying or impingement drying (air foils) may be added as process steps. Overall, paper production tends to use more thermal energy than electric power.

As pulp and paper production is an energy intensive industry, investments into new and advanced energy systems can pay off economically and ecologically in the medium term. Usually, different solutions are reviewed whenever increases in production demand higher rates of heat and electric power. Furthermore, whenever large investments like major overhauls or renewal of major components of energy systems are required, it is recommended that current technological options are reviewed and the products available from various OEMs (original equipment manufacturers) are compared. This should be done well in advance in order to include technologies and OEMs with longer lead times in the consideration.

Pulp and paper sites wishing to reduce energy costs and their environmental footprint in the short term should aim to reduce their energy demand, for example by decreasing the moisture content of the paper upstream of the drying section, optimizing their vacuum system [1] or increasing the share of recycled fibers in the end product.

Pulp and paper production requires both heat and electric power. Whereas electricity can either be sourced from the electric grid or produced locally, high temperature heat cannot be distributed via networks due to unacceptably high heat losses. Therefore, heat has to be generated locally. Pulp and paper producers can either source electricity from the public grid and generate heat separately or use a combined heat and power (CHP) process to generate both locally. The latter yields much higher total efficiencies than the former, leading not only to a reduced environmental footprint, but also to lower costs.

CHP energy systems can be based on gas turbines, steam turbines or internal combustion engines, or on a combination of these.

Some pulp and paper production processes produce not only the desired product, but also byproducts with high calorific value. These processes will usually be the first choice as the primary energy source. In all other cases, the selection of a primary energy source will be closely linked to availability and prices, both of which may vary over time and will depend on the region. The following sections will consider these general aspects.

Primary energy sources for pulp production

The selection of the primary energy source is largely dependent on the availability of an affordable fuel in significant quantities. In pulping, the available energy sources differ widely between production processes.

Kraft pulping

Kraft pulping separates lignin from the fibers using the liquor cycle, which produces lignin dissolved in black liquor together with primary fibers as joint products. In consequence, as lignin has a high heating value, the regeneration of black liquor serves as an abundant source of primary energy. Although black liquor is a liquid fuel, its use in energy conversion is limited to simple atmospheric combustion processes due to the residual inorganic smelt. As an alternative, the black liquor may be treated in a gasification process in order to produce flue gas [2]. Although this requires an additional investment, it will permit the gaseous fuel obtained to be used flexibly in a wide range of energy conversion machinery.

In facilities with integrated debarking and chipping, other joint products can include bark, pin chips and fines, which can also serve as fuels. Since they are solid fuels, they are also suitable only for atmospheric combustion.

In non-integrated pulp production, the combustion of black liquor will usually yield more energy than needed for the pulp production process. The surplus energy can be sold to external consumers after conversion into a suitable form. The sale of electricity and/or heat is found frequently in kraft pulping plants. As the energy conversion is synchronized with the production process, the supply of electricity or heat to external consumers is usually provided at a constant rate, also called base load. With increasing volatility of electricity prices, feeding the base load into the grid becomes less profitable. On the other hand, the demand for peak load and alternative fuels is rising. Consequently, market conditions foster energy storage and improve the profitability of Power-to-X conversion (PtX). OEMs of energy conversion equipment offer a wide range of conversion and storage facilities, for example for the production of hydrogen or synthetic methane [3].

Mechanical pulping

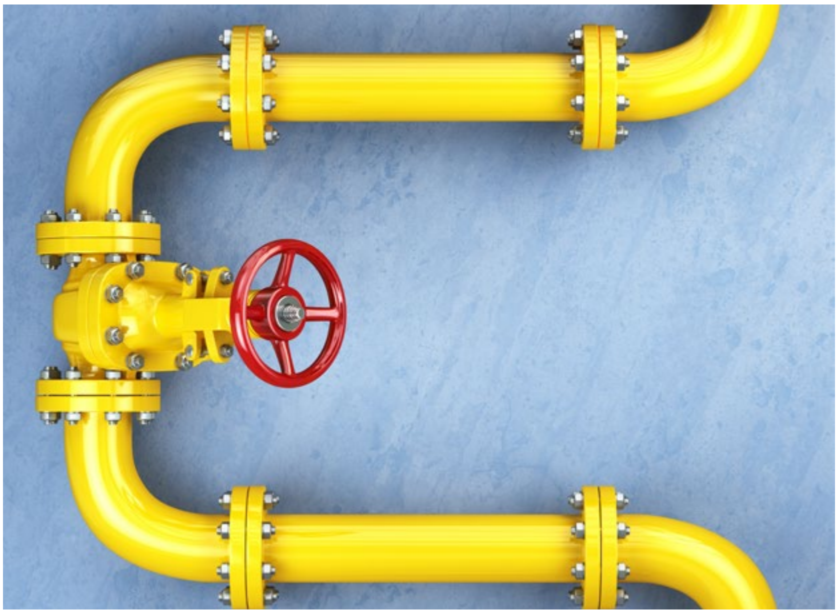
Bark, and possibly fines, may serve as the primary energy source to fulfill some of the fuel demand of mechanical pulping. If the demand for process energy surpasses the available quantities of these solid fuels, operators might use additional solid fuels such as coal-based fuels, refuse-derived fuels or agricultural biomass, due to the commonalities in the combustion process between all of these fuels. While biomass and refuse-derived fuel are regarded as having small carbon footprints, coal-based fuels are becoming less favorable over time both economically and in public acceptance. Should no additional biomass or refuse-derived fuel be available in sufficient quantities, natural gas will limit not only greenhouse gas (GHG) emissions, but also emission of other pollutants like soot, dust, CO and NO_x .

Sulphite pulping

The less common sulfite pulping most often uses a production process with a liquor cycle. Although important differences between sulfite and kraft pulping chemistry exist, as in kraft pulping, liquor combustion will provide large quantities of chemical energy derived from lignin. Therefore, the primary energy sources will resemble those used in kraft pulping.

Primary energy sources for paper production

In many regions, paper production is separated from the production of fresh fibers in the pulping process (non-integrated paper production). However, other production facilities integrate pulping with papermaking (integrated paper production). Sourcing of primary energy differs greatly between integrated and non-integrated paper production.



Integrated Paper Production

Whenever paper is produced in the same facility as chemical pulp, the surplus energy of the liquor-based CHP will also fulfil some of the energy demand of the paper production.
In consequence, the primary energy required to complement the combustion of liquor should be selected as described for the non-integrated production of pulp.
On the other hand, the primary energy source for paper production integrated with mechanical pulping will resemble the solutions for the non-integrated production of paper.

Non-integrated paper production

The potential for the production of primary energy sources on-site is limited in non-integrated paper production. Usually, a separate source of primary energy is required. As large amounts of heat and power are used in paper production, fuels with high calorific values are needed.

Sourcing electricity and heat from nearby nuclear power plants has, so far, been a feasible solution only for a few paper production facilities due to lack of availability and low public acceptance. As electricity is usually too expensive for use as a direct heat source in power-to-heat units, chemically stored energy is the most important primary energy source.

Refuse-derived fuels are often inexpensive but can impose a high workload on operational personnel. Their combustion generates significant amounts of air pollutants, reducing public acceptance and requiring a complex exhaust gas treatment. Hard coal or lignite show similar advantages and disadvantages but are additionally prone to sanctions on CO_2 emissions in many regions, increasing operational costs. The carbon footprint of solid biomass is regarded as low, but limited availability in volume will usually prevent its use as the sole primary energy source. The mixed use of different solid fuels can increase the flexibility of the plant but poses significant challenges to system control due to the differences in calorific values of the different fuels. Solid fuels can be stocked, but the associated vehicle-based delivery infrastructure is more prone to infrastructure disruptions than pipeline-based gaseous fuels.

Liquid fuels can easily be stocked and provide constant fuel properties. These advantages usually lead to high liquid fuel demand for transportation purposes (e.g. road, air, rail and maritime traffic) and result in high prices in most regions of the world. For economic reasons, this therefore makes them less suitable for energy-intensive industries like paper production. However, in case of interruptions of the fuel supply, liquid fuels can be used as a backup in dual fuel power plants. Furthermore, operators of dual fuel units can adapt quickly to changes in price level.

Natural gas is increasingly regarded as a low-carbon transition technology and reduces personnel workload due to the automated operation of the plant. Emissions of noise and other air pollutants such as soot, dust, CO and NO_x are low, making it a preferred choice in the vicinity of residential areas and nature reserves. The transport of liquid natural gas (LNG) via ship has recently diversified the availability of gas from different regions and contributes to its constant availability.

Paper factories usually treat their wastewater from the production process in a dedicated treatment unit. This unit relies either on aerobic or on anaerobic processing. Whereas aerobic processing produces no fuel, anaerobic wastewater treatment produces low calorific sewage gas in small quantities. Mixed with natural gas, its use reduces both the costs and the carbon footprint of the plant.

Recent trends in politics and society foster the use of green hydrogen as a carbon-free energy source. The color “green” denominates its generation using renewable energy sources only. Green hydrogen is expected to partly replace natural gas in the pipeline network; an admixture of up to 20 vol-% in the next few years is projected in some parts of the world. Operators can prepare for such changes by selecting an energy system that can handle such ratios of hydrogen fuel. Plans exist for the construction of dedicated green hydrogen pipeline systems in regions with a high density of energy intensive industries. Paper producers should therefore inquire if retrofits for 100% hydrogen will be available for their energy systems on time, as utilities are increasingly investing in green hydrogen generation capacities. Well-designed hydrogen combustion systems keep all relevant process parameters equivalent to those for natural gas despite the change of fuel, i.e. exhaust-gas temperature at full and part load, maximum electric power output, and emissions at full and part load [4]. These properties ensure full suitability, flexibility, and adherence to environmental regulations.

Suitability of energy systems

CHP coefficient

One important characteristic of energy systems is the CHP coefficient, i.e. the ratio of power to heat. Typical for the paper industry is a high heat demand, translating to CHP coefficients much lower than 0.8 [5]. The most economical solutions for CHP coefficients lower than 0.8 are gas turbines [6], whereas higher CHP coefficients, which occur in other industries, would make gas engines economically more attractive.

Exhaust-gas temperature

High exhaust-gas temperatures at the boiler inlet are necessary in the paper production process in order to efficiently produce saturated or slightly superheated (SH) steam at the highest pressures levels required. These temperature levels can only be provided by some technologies. Gas engines, for example, are usually limited to supplying hot water for heating purposes. In some cases, they are used to produce steam at pressures of up to 3 bar. The low exhaust-gas temperature is thermodynamically disadvantageous, as shown in Figure 1. The total efficiency of steam cycles with a low exhaust-gas temperature is limited by their high stack temperature. This is caused by pinch point constraints at the transition between the Economizer (Eco) and the Evaporator as shown in Figure 1 (light blue line). As a consequence, large quantities of heat are released into the atmosphere, translating into high heat losses. As apparent in Figure 1, the higher exhaust-gas temperatures from gas turbines will permit the outlet temperatures at the stack (red line) to be decreased. This increases the total efficiency. The effect described increases with the shifting of the pinch point to increasing evaporation temperature levels. For paper production processes with maximum steam pressures that can reach between 5 and 15 bar, or even 20 bar, gas turbines with exhaust-gas temperatures in the range of 500 °C [7] combined with waste heat recovery boilers are indispensable components of energy systems with high total efficiencies. Supplementary firing is a proven technology to further increase the exhaust-gas temperatures, total efficiencies and heat quantities of gas turbines. With gas engines, however, supplementary firing can be challenging due to pressure fluctuations in the exhaust gas.

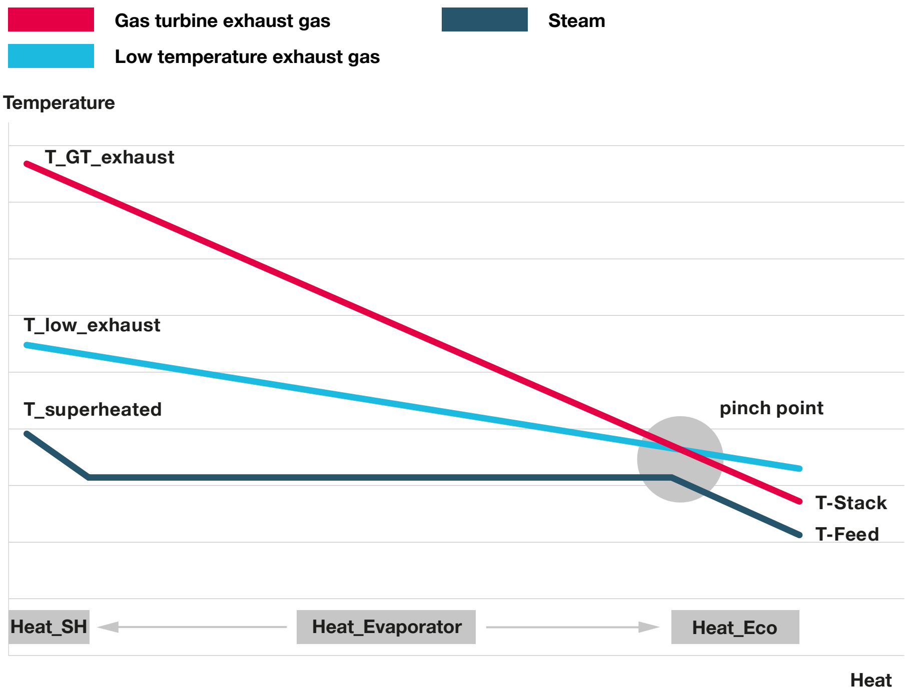


Fig. 1: Heat-Temperature diagram of steam process through waste heat recovery unit

Steam pressure reduction

Most paper production facilities use two or three different steam pressure levels with saturated steam for the drying section. It is common practice to produce steam at the highest required pressure and use either steam pressure reduction units or small steam turbines to provide the required lower pressure levels. Steam turbines need additional capital investment compared to pressure reduction units but increase the electrical efficiency of the energy system. This makes them the preferred choice in times of increasing energy prices and environmental protection efforts.

If steam is produced at high pressures in the range of 70 bar, larger steam turbines can also be used to supply the production facility with electric power while expanding the steam to the required pressure levels. However, as steam pressures in this range need a water-tube boiler, close attention should be paid to the economic evaluation of high-pressure steam cycles due to the high capital investment.

Part-load capability

Although pulp and paper mills operate at full load most of the time, the reduction of product output due to maintenance or reduced market demand cannot always be avoided. Consequently, energy demand for both electricity and heat will decrease temporarily, but process parameters need to be kept constant to ensure the quality of the products. When selecting an energy system, operators should therefore consider selecting an energy system which provides stable exhaust-gas temperatures at part load.

Availability of energy

Profitable production with a high output and optimal quality requires a continuous production process, which needs a stable energy supply. This supply relies on the one hand on the availability of primary energy. On the other hand, the availability of the energy system itself is of great importance. Its careful selection can prevent arduous trouble shooting for operation personnel and relieve the management of difficult decisions. Some production facilities use an energy system consisting of multiple units (e.g. of 2 x 50% of the required nominal power) in order to increase availability and flexibility, as seen also across different industries [8]. Especially if the total electrical power demand can be split into units larger than 5 MW, the significant benefits in availability and flexibility may outweigh the small decrease in efficiency and increase in costs associated with multiple smaller units. Paper factories with high connection capacity to the electric grid may design their power plant in such a way that it is able to produce heat without producing electricity. Gas turbine powered facilities can utilize waste heat recovery steam generators equipped with supplementary firing and fresh-air blowers as a back-up for the heat supply from the gas turbine. This permits them to generate steam in the event of gas turbine downtime, and source electricity from the grid, keeping production running.

Unscheduled downtimes

The availability of energy systems is based on two aspects: scheduled and unscheduled downtimes. Unscheduled downtimes are difficult to assess beforehand. Fortunately, many suppliers have decades of operational experience. The robust design of equipment based on this extensive experience will usually reduce unscheduled downtimes to a minimum, shifting the focus to service quality and scheduled downtimes.

In order to assess the likelihood of unscheduled downtimes, operators often focus on references to evaluate the maturity of the energy system and its components. However, technological advances in terms of ecology, economy or flexibility may preclude extensive operational experience. Therefore, operators should balance their requirements in accordance with their preferences and use complementary means of evaluating reliability. It can be helpful to seek direct contact with operators of existing units of the types of interest. Their experience with reliability will yield valuable insights. If unforeseen issues should arise, the swift reaction of the after-sales organization of the OEM is of the utmost importance. Experienced operators of the energy system of interest can advise on this as well.

Operators should ask suppliers about diagnostic measurement systems available, which will predict the need for unscheduled maintenance activities. Such “predictive maintenance” systems can convert unscheduled downtimes into scheduled downtimes, permitting them to be scheduled in alignment with factory shutdowns. Furthermore, the service organization is notified beforehand and can assign personnel and spare parts well in advance, reducing the duration of the downtime.

Scheduled downtimes

Since energy systems need to be shut down for maintenance, referred to as scheduled downtime, its frequency and duration have a high impact on availability. Advanced maintenance solutions with short durations of maintenance-induced downtime and long periods of continuous operation in between reduce disruption of production. Some energy systems have very short maintenance downtimes, allowing their maintenance to be scheduled in parallel with that of the production equipment. In this case, energy system maintenance will not cause any production downtime.

Service quality

Pulp and paper production is a challenging business and consumes most of the manufacturers' attention. Its process technology is sensitive to disturbances. The energy supply should therefore be a secure and reliable background process.

Maintaining high health and safety standards requires a service partner who is familiar with the energy system equipment and its original spare parts. Good service also includes offering retrofit options in order to adapt to changing requirements and to governmental regulations.

In the case of urgent issues, troubleshooting assistance for energy equipment needs to be available quickly in order to maintain or restore the energy supply. A competent and dependable OEM service, preferably with dedicated personnel, will be familiar with the equipment and expedite the identification and implementation of a solution in the most effective way.

24/7 hotlines will relieve power plant operation personnel of stress and workload. Operators are also advised to consider the geographical proximity to well-equipped service hubs to support and accelerate workshop activities. Sharing a common language can aid rapid problem solving.

Pulp and paper producers are advised to consider long-term service agreements covering a comprehensive scope, for example maintenance and repairs together with guaranteed response times. These long-term contracts reduce the workload by relieving personnel from frequently negotiating new contracts and ensure predictable expenses for many years.

Pulp and paper producers can use these contracts to transfer technology-associated risks to the OEM of the energy system components. Energy system maintenance intervals should be long and maintenance durations short. Maintenance should be scheduled flexibly in order to allow alignment with paper production machinery maintenance as described in the "Availability" section. Many paper factories concentrate their maintenance during the winter holiday season. Advance clarification of service personnel availability for this period can be beneficial.

Service hubs of MAN Energy Solutions

Energy costs

Due to the high energy costs and high requirements placed on the energy management system, cost-efficient energy systems and continuing improvements are a necessity for the pulp and paper industry. In the economic evaluation, all direct and indirect costs incurred during the lifetime should be included. Besides procurement costs for the prime mover and its primary energy input and auxiliary materials, this includes auxiliary systems and required modifications of existing buildings and installations as well as costs for commissioning and maintenance. In addition, the resilience to changes in market conditions should be evaluated.

Pulp and paper production facilities often have a long heritage. Integration of a new energy system into an existing factory, also known as brownfield installation, is a challenge for suppliers. This may cause additional high costs for the integration of new energy systems. Competent suppliers will be able to provide references for previous brownfield installations [9] and inform the customer how to limit the cost of modifying existing infrastructure.

Energy systems consist of a large number of components. This makes commissioning a challenge for all stakeholders. Energy systems that consist of pre-assembled, packaged units are faster and therefore cheaper to install and commission and pose considerably less risk of experiencing time-consuming and expensive commissioning challenges [10].

During the economic evaluation, not only design point operation plays an important role, but part-load performance should also be considered. During maintenance of the pulp or paper production equipment, heat and electricity demand will be reduced. Product changeover can also temporarily reduce energy demand. Changes in market conditions can influence the demand of product properties and quantities as well, affecting energy demand for shorter or longer time frames.

As a starting point, payback times for energy systems depend on individual factors and can be evaluated by energy consultants, EPCs (engineering, procurement, and commissioning companies) or by OEMs of turbines and engines. Typical assessments for different types of equipment used in the paper industry are available. OEMs, EPCs and energy consultants will assist with updating those assessments using individual boundary conditions given by the operator, for example actual fuel prices. An example of such an evaluation is offered in the case study below.

Operators need to be aware of the challenge of weighing up the economic evaluation against the equally important non-quantifiable factors mentioned in the other sections, for example emissions and service response time. Non-economic factors and their practical impact on continuous and flexible production may prove to be more important for the profitability of the site than the economic evaluation itself, as production downtime can accumulate losses of tens of thousands of dollars within a few hours.

Environmental impact

The environmental footprint plays an increasingly important role for the paper industry:

- Legislation sets tight limits
- The importance of public acceptance is increasing, especially for paper factories near residential areas
- A greener image can boost the sales of paper products to end users
- Investors prefer sustainable businesses
- Employees prefer to work on sites with high health and safety standards and
- Climate change can affect pulp and paper production directly by diminishing essential water resources

It should be pointed out that the selection of the type of energy system and the model of the core units both play a vital role. CHP systems reach high total efficiencies and will usually be the solution with the smallest environmental footprint for pulp and paper. Core units can be selected by considering emissions of air pollutants, CO_2 emissions and total efficiency, noise emissions and water consumption. Many investors will assess the environmental impact based on common evaluation criteria. As an example, the EU Taxonomy categorizes renewable energy sources such as biogas or green hydrogen as well as natural gas and nuclear energy as being in line with environmental objectives [11].

A low level of emissions indicates an advanced overall technological level of combustion systems. Besides manufacturers' specifications and guarantees, real-life values based on the actual operating behavior confirm the environmental footprint of energy systems. On-site-visits to units in commercial operation or to units active on a test bed allow technical properties to be witnessed and confirmed. When travel to the supplier's production site is not possible, video calls can transfer remote measurement data.

The operating permit for an energy system often focuses on the level of emissions of gaseous pollutants. The formation of carbon monoxide (CO) and nitrogen oxides (NO_x) are a challenge for all combustion systems. Advanced combustion technologies reach NO_x levels below 10 ppm (parts per million), also known as “single digit” emissions, without using exhaust-gas treatment in full-load and well into part-load operation. The installation of systems with such emission levels should permit the official approval in all parts of the world and meet emission regulation requirements for the foreseeable future. Operation without exhaust-gas treatment reduces susceptibility to its failure as well as reducing capital investment and operational costs. Low emissions in part-load operation points allow flexible operation. Operation with gas turbines without blowing off air increases efficiency. This increased part-load efficiency improves economic and environmental performance through lower operational costs and reduced CO_2 emissions.

Soot emissions are visible to the public and cause public protests, which may influence the approval process of the local authorities. Gaseous fuels preclude the formation of soot, and advanced combustion systems can burn liquid fuels without visible soot emissions. Solid fuels may need exhaust gas treatment to reach the same level, requiring capital investment and frequent maintenance, and posing the risk of component failure.

Repeated exposure to noise levels above 85 dB(A) can lead to hearing loss among employees. Above this level, hearing protection is strongly recommended and mandatory in many regions of the world. Even below this level, oral communication may already be impeded. Residents in the vicinity of production sites often oppose elevated noise levels. Solid fuels are usually associated with noise emissions from traffic and handling. Energy systems using gaseous or liquid fuels are much quieter than those burning solid fuels and thus usually stay below 85 dB(A). Operators wishing to improve the health and safety of their employees even further should ask OEMs about optional lower noise emission levels.

Pulp and paper mills rely on the availability of water as a process medium. Although sites are usually located in areas with adequate availability of water, climate change has already, and will increasingly, reduce the amount of water available. Some combustion units inject water into the combustion system in order to lower emissions of NO_x. Not only can the consumption of water be reduced using state-of-the-art dry combustion systems, which do not require any water injection regardless of the type of fuel being used, but dry combustion also omits the corresponding components, eliminating any susceptibility to failure.

Case study

Technical and economic evaluation of combined heat and power solutions

A technical and economic evaluation of combined heat and power systems for the pulp and paper industry is presented here. This study considers a gas turbine of 8 MW class, namely the MGT8000, combined with a heat recovery steam generator (HRSG).

The evaluation is based on the technical and economic boundary conditions given in Table 1 and Table 2. The economic evaluation is carried out with an average annual ambient temperature of 15 °C. The main parameters are based on the data given in Table 2.

Parameters	Data
Altitude [m]	0
Relative humidity	60%
Inlet pressure losses [kPa]	0.75
Outlet pressure losses [kPa]	2.5
Load [%]	100
Ambient temperature [°C]	15
Electrical power output of the gas turbine [MW]	8.21
Electrical efficiency of the gas turbine [%]	33.6
Exhaust temperature of the gas turbine [°C]	520
Exhaust gas flow of the gas turbine [kg/s]	28.4
Average electrical power demand [MW]	7.0
Steam demand with & without supplementary firing [t/h]	16.0 .. 35.0
Steam pressure [bara]	17
Feed water temperature inlet HRSG [°C]	90
Make up water temperature [°C]	20
Condensate return fraction [%]	70
Condensate return temperature [°C]	90
Ambient temperature range for the evaluation [°C]	-10 .. 40
Lower heating value (nat. gas) [kJ/kg]	48,000
Conventional gas fired boiler efficiency [%]	90
Average CO_2 emissions from electrical power grid in Europe [g/kWhe]	450
CO_2 emissions from conventional gas fired boiler [g/kWh_nat.gas]	220

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

Parameters	Data
Electricity prices bought from the grid [€/MWh]	38, 60, 100, 121, 219
Natural gas price [€/MWh]	33
Interest rate [%]	5
Yearly operating time [hours]	8,400

Table 2: Economic boundary conditions

Depending on site location and future price trends, industrial customers may face different electricity prices. Therefore, the economic evaluation of the combined heat and power solutions is presented for different industrial electricity prices. The average European electricity price is 121 €/MWh [12], the highest price is 219 €/MWh and the lowest is 60 €/MWh. The range of electricity prices evaluated, between 38 and 219 €/MWh, will furthermore give readers in all parts of the world a useful indication. This evaluation thus indicates the viability of the solution in actual current markets. The average European natural gas price [12] is considered as a baseline. This fuel price provides an indication for the medium term and is also at the level of many countries world-wide. The variation of the electricity prices show their influence on the profitability of combined heat and power systems.

Description of the combined heat and power system

The presented CHP system for the pulp and paper industry produces steam and electric power based on a topping cycle with a gas turbine as prime mover (Figure 2). The exhaust heat generated by the gas turbine drives a Heat Recovery Steam Generator (HRSG) for steam production at 17 bar(a). Two options are evaluated. The first is without supplementary firing (unfired). In this case, the steam process corresponds to the maximum steam production possible with the available exhaust heat of the gas turbine. The second option is with supplementary firing (fired). In this case, a supplementary firing is included between the gas turbine and the HRSG unit. The design of the supplementary firing has been chosen to approximately double the steam production compared to the unfired process [6, 13, 14]. The supplementary firing increases the exhaust-gas temperature and enables a significant increase in steam production. The steam process parameters considered in this study are typical of those used in the pulp and paper industry.

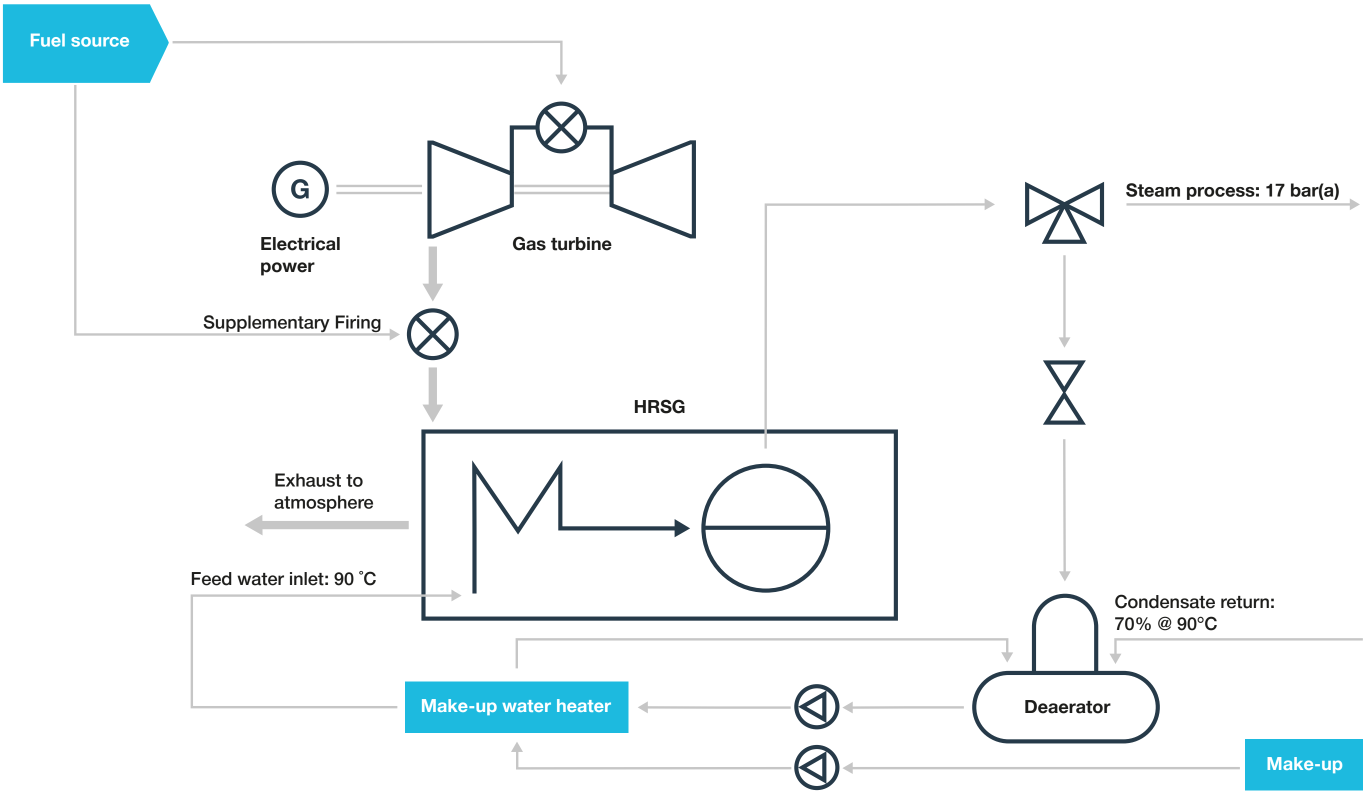


Figure 2: Configuration of the combined steam and power cycle

The size of HRSG for the unfired case differs significantly from the size of that used with supplementary firing. The reason is that, in general, the components of the HRSG with supplementary firing such as the evaporators and economizers are larger compared to those without supplementary firing. Both designs are standard for steam boiler OEMs [13, 15, 16]. It is assumed that the combined steam and power system operates continuously at almost full load. It is equally assumed that the steam generated is fully consumed on site but that the difference of electrical power between that produced and that consumed is sold to the grid at the same electricity price given in Table 2. In reality, the excess power is sold to the grid at a lower price but considering the fluctuations of the electricity price during a typical day, the average of the electricity price paid and the price achieved on selling excess power to the grid are almost equivalent.

Technical evaluation

The main results of the evaluation of the combined heat and power solutions focus on the following parameters:

- The profiles of the electrical power output and steam production
- The profiles of the efficiency of the electrical, steam and combined heat and power generation

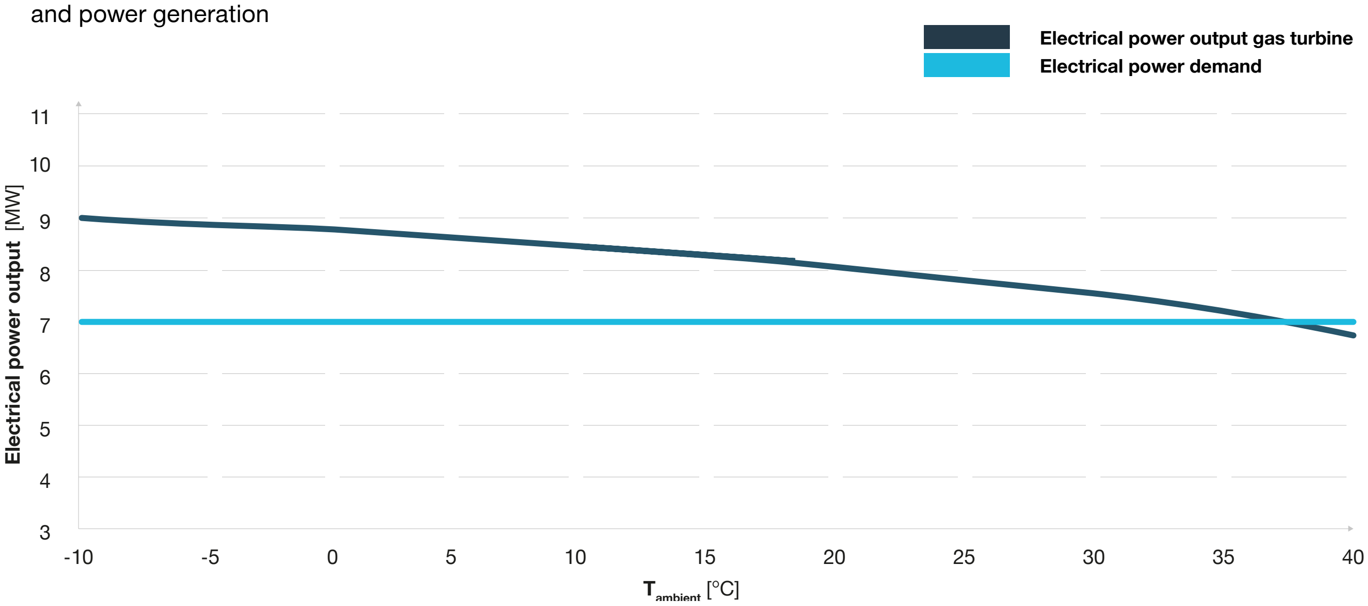


Figure 3: Evolution of electrical power output of the gas turbine and the electrical power demand with the ambient temperature

Figure 3 shows the profile of the electrical power output of the gas turbine and the profile of the electrical power demand of the plant as a function of the ambient temperature. The electrical power demand is constant and equal to 7 MW. As is typical of gas turbines, the electrical power output decreases from approx. 9 to 6.7 MW when the ambient temperature increases from 10 to 40 °C. In general, the electrical power output of the gas turbine covers the electrical power demand for an ambient temperature lower than 37 °C. The excess electrical power produced is sold to the grid.

When the ambient temperature is higher than 37 °C, the electrical power output of the gas turbine is slightly lower than the electrical power demand. The small quantity of additional electrical power required is bought from the grid. This case only occurs for a very short operating time.

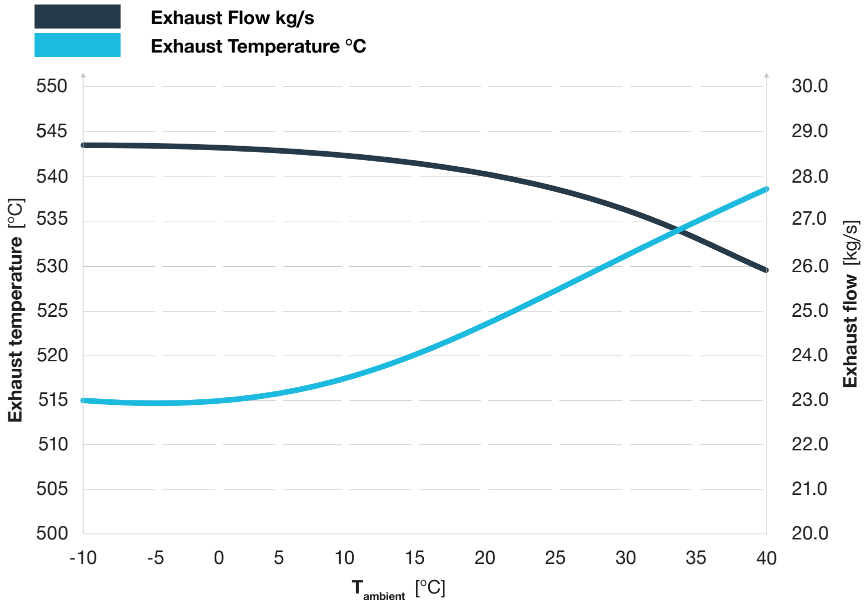


Figure 4: Profile of the exhaust flow and the exhaust temperature with ambient temperature

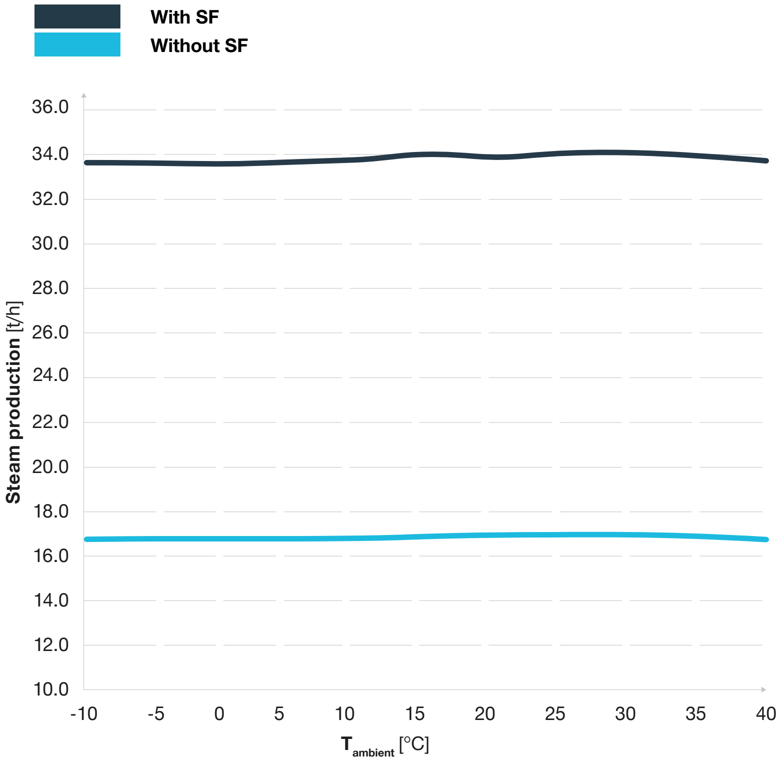


Figure 5: Profile of steam production with ambient temperature

Figure 4 shows the change in the exhaust parameters of the MGT8000 with change in ambient temperature. The increase of the ambient temperature from -10 to 40 °C implies the increase of the exhaust temperature from 515 to 537 °C. The exhaust flow shows the opposite behaviour and decreases from 28.7 to 26 kg/s when the ambient temperature increases. The combination of these exhaust parameters results in an almost constant thermal power over the ambient temperature range. This result leads to a constant rate of steam production at 17 t/h independent of ambient temperature as depicted in Figure 5.

Concerning the supplementary firing (SF) case, the steam production has an identical evolution to the unfired case, but it is at a level of 34 t/h (Figure 5). Unlike the electrical power generation, the behaviour of steam production with and without supplementary firing is independent of the ambient temperature. Note that the combination of the exhaust parameters of the MGT8000 gas turbine (Figure 4) provides the best solution for the pulp and paper industry and for steam production with and without supplementary firing. This balance may be different for other types of gas turbines, which may result in changes in the steam production.

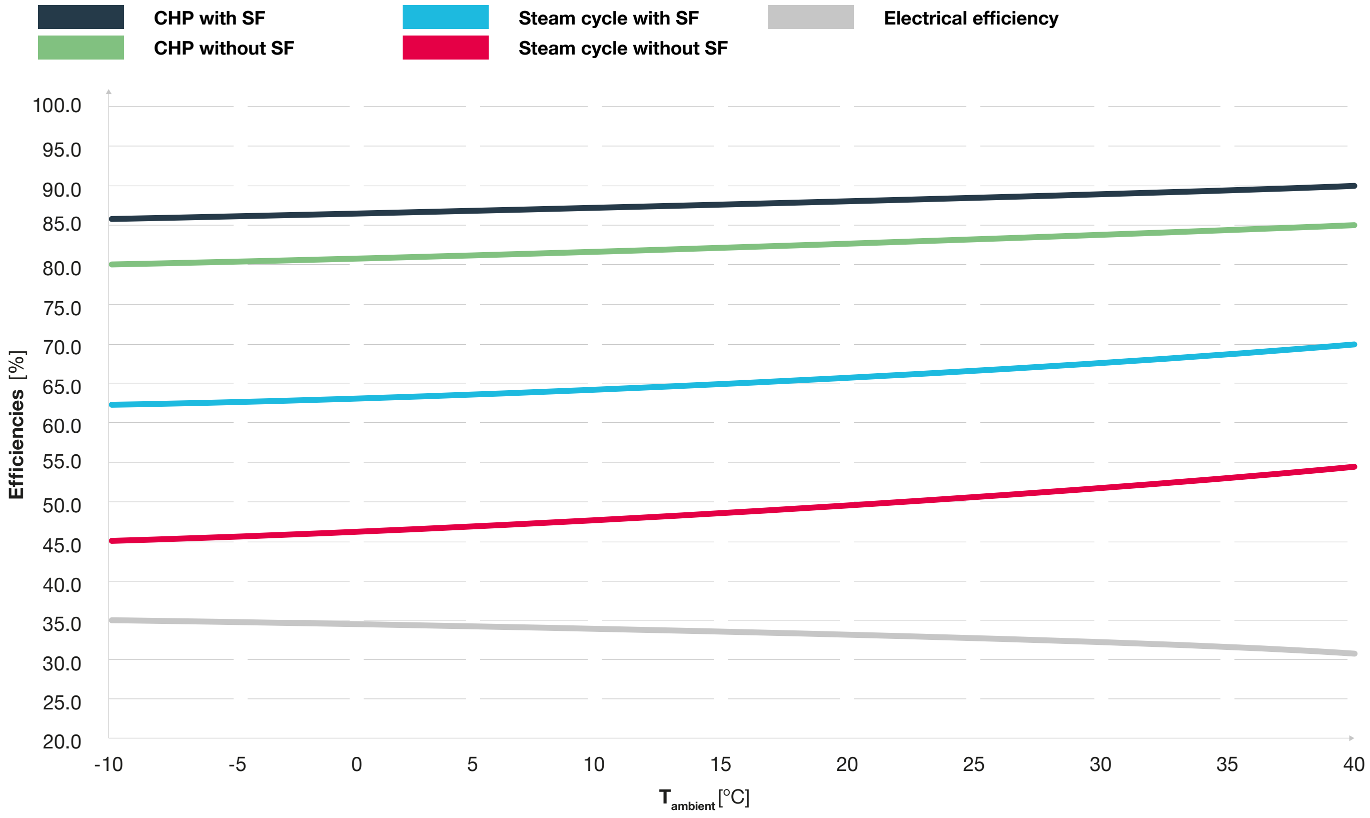


Figure 6: Evolution of the electrical, steam and overall combined heat and power efficiencies with ambient temperature

Figure 6 shows the electrical, steam and CHP efficiencies against ambient temperature for the unfired and supplementary fired cases. The electrical efficiency decreases from 34.7% to 31.1% when ambient temperature increases from 10 to 40 °C. This trend is identical to that of the electrical power (cf. Figure 2). The efficiencies of the steam process and the overall combined steam and power cycle both display the same trend. This can be attributed to the fact that the overall process is heat- rather than power-driven, i.e., the effects on the steam process outweigh those on the gas turbine in the overall assessment [13]. These efficiencies increase when ambient temperature increases. In the ambient temperature range considered, for the unfired case, the steam process efficiency increases from 45% to 54%. For the fired case, the efficiency of the steam process increases from 62% to 70%. The steam process efficiencies for both fired and unfired cases are lower than the conventional boiler efficiency of 90%. The reason is that the steam process efficiency is evaluated with the total fuel consumption of the CHP plant. However, the whole fuel consumption of the CHP system is shared between the electrical power process and steam process. The overall CHP efficiency increases for the unfired case from 80% to 85% when the ambient temperature increases from 10 to 40 °C. For the fired case the overall CHP efficiency increases from 86% to 91%.

NO_x and CO emissions results

Table 3 provides the NO_x and CO emissions of the evaluated CHP systems. For the unfired case, the NO_x and CO emissions are identical to those of a gas turbine in a simple cycle. The NO_x and CO emissions are slightly higher for the case with supplementary firing than those of the unfired case due to the additional emissions of the supplementary firing equipment. These results show that both fired and unfired CHP plants provide very clean electrical power and steam processes.

Emissions results are referenced to 15% oxygen, dry and at ISO-conditions

Solution type	Without supplementary firing	With supplementary firing
NO_x	9 ppm (18 mg/Nm³)	15 ppm (29 mg/Nm³)
CO	16 ppm (20 mg/Nm³)	19 ppm (24 mg/Nm³)

Table 3: NO_x and CO emissions of CHP system with and without supplementary firing

Reduction of CO_2 footprint

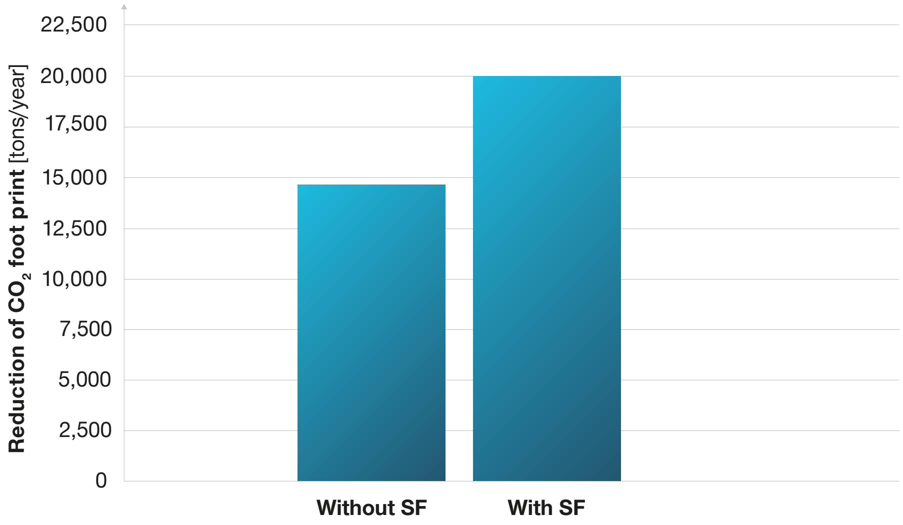


Figure 7: Reduction of CO_2 footprint

Figure 7 shows the reduction of the CO_2 footprint of the CHP solutions evaluated with and without supplementary firing. The reduction of the CO_2 footprint is the result of a comparison with the conventional solution that is defined as: buying electrical power from the grid and covering the steam demand by a gas-fired boiler. The reduction of the CO_2 footprint is attributed to the benefits of using one fuel source for both the electrical power and steam processes.

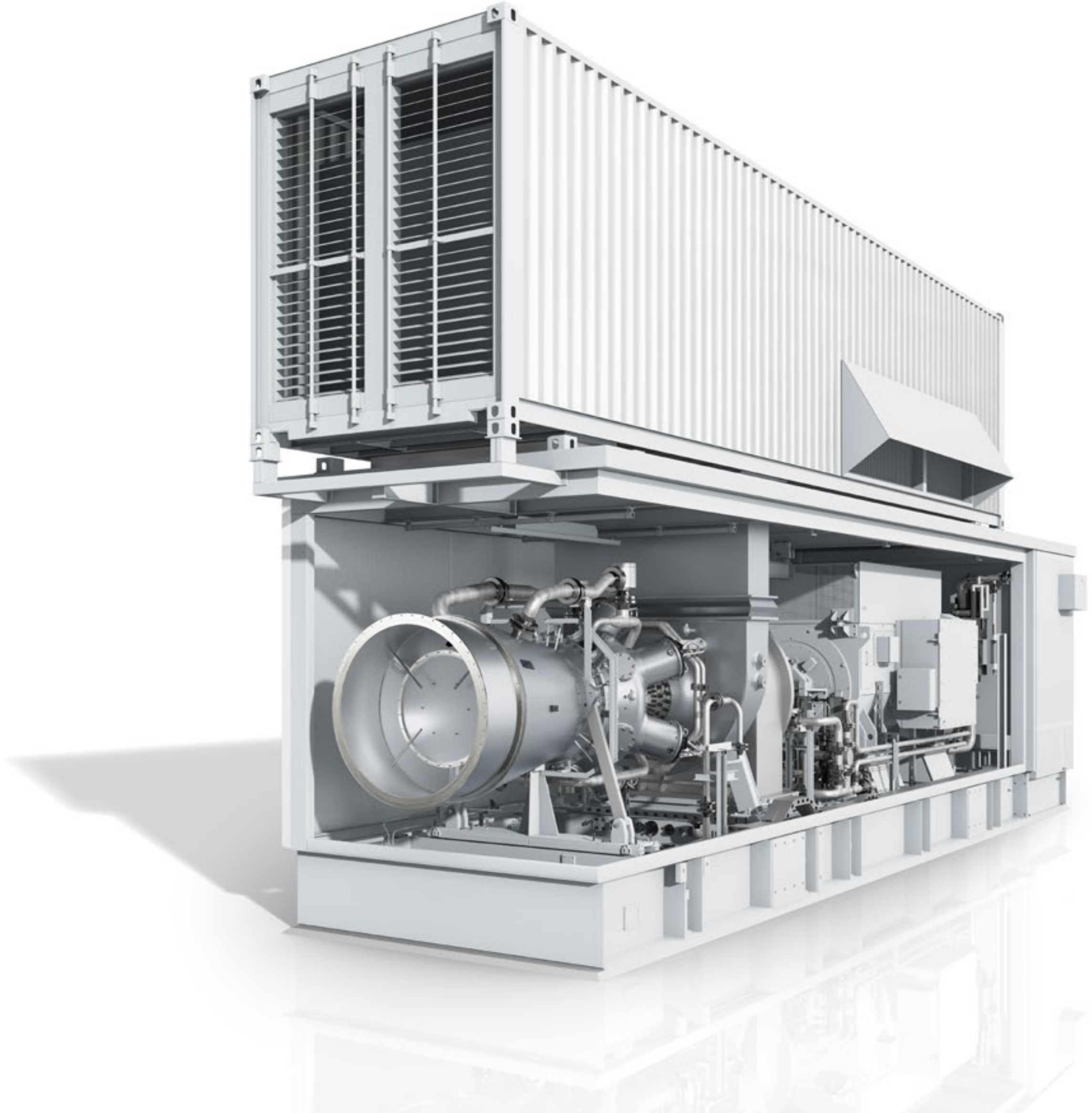
The reduction of the CO_2 footprint of the CHP solution without supplementary firing is 14,770 tons/year, that is 27% fewer CO_2 emissions than the conventional solution. For the solution with supplementary firing, the reduction of the CO_2 footprint is 20,150 tons/year, which is 25% fewer CO_2 emissions than the conventional configuration. Putting this in perspective, one can look at the standard CO_2 emissions for a car that amount to 120 g/km.

Considering the average mileage of a car as 13,500 km per year and the annual operating time of the plants specified above, the CO_2 reduction of the CHP solution without supplementary firing is equivalent to the CO_2 emissions of more than 9,000 cars and that of the fired solution equivalent to more than 12,000 cars.

Economic evaluation of combined heat and power solutions

The objective of the economic evaluation is to quantify the benefits of the studied combined steam and power systems. The conventional configuration of electricity supply from the grid and steam generation using conventional gas-fired boilers serves as a reference for the costs.

The difference between the operating costs of the CHP solution and those of the conventional system constitute the net yearly savings (benefits) of the CHP system. The operating costs of the CHP plant include the fuel costs and maintenance. The costs for CO_2 certificates were not taken into account in the economic analysis, but in principle these costs can have significant impact on the benefits of the CHP system. At the time zero, the net cashflow is equal to the negative value of the capital expenditure of the plant. The accumulation of the net yearly savings over time represents the net cashflow. For the defined lifetime of the CHP cycle, the net cashflow constitutes the net present value. The dynamic payback time directly depends on the interest rate, the net yearly savings and the total investment in the CHP solution. The investment in the CHP plant includes the capital expenditure for the gas turbine, boiler, auxiliaries, and the installation and commissioning.



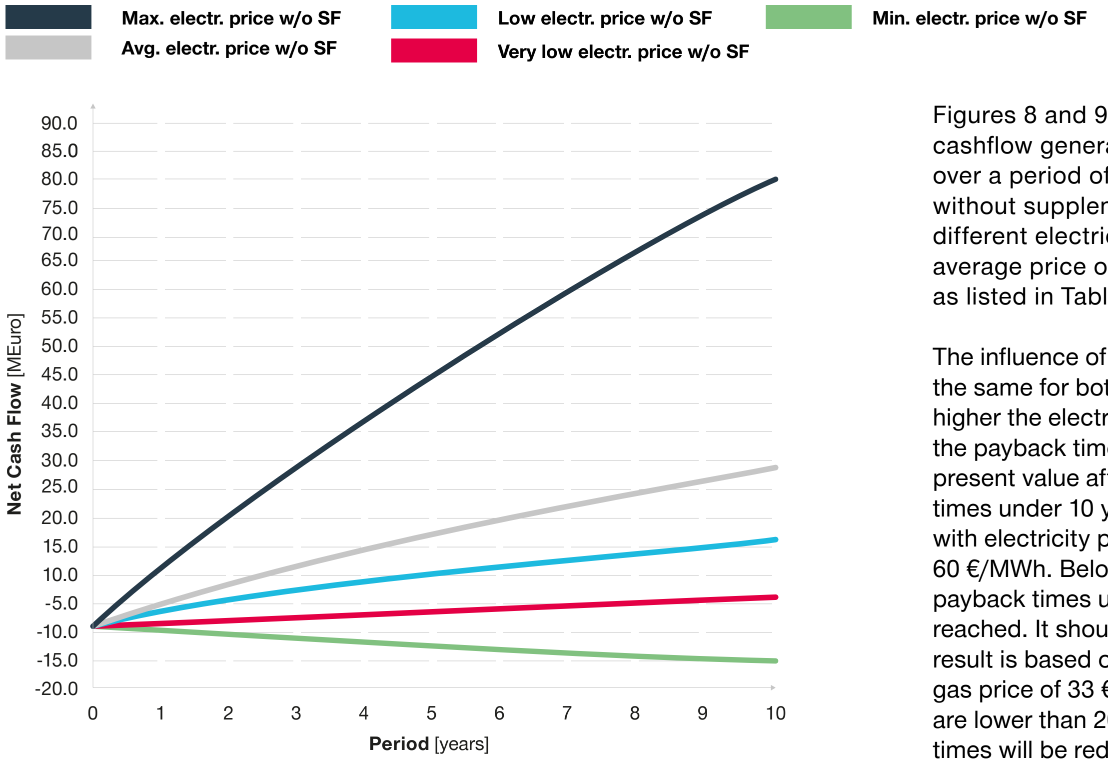


Figure 8: Influence of electricity price on the net cashflow over a period of 10 years for a CHP plant without supplementary firing

Figures 8 and 9 show the net cashflow generated by the CHP plant over a period of 10 years with and without supplementary firing for different electricity prices and the average price of natural gas in Europe as listed in Table 2.

The influence of the electricity price is the same for both evaluated cases. The higher the electricity price, the shorter the payback time and the higher the net present value after 10 years. Payback times under 10 years will be reached with electricity prices higher than 60 €/MWh. Below 100 €/MWh, even payback times under 5 years will be reached. It should be noted that this result is based on the average natural gas price of 33 €/MWh. If gas prices are lower than 20 €/MWh, the payback times will be reduced to less than 5 years even if the electricity prices are substantially lower than 100 €/MWh.

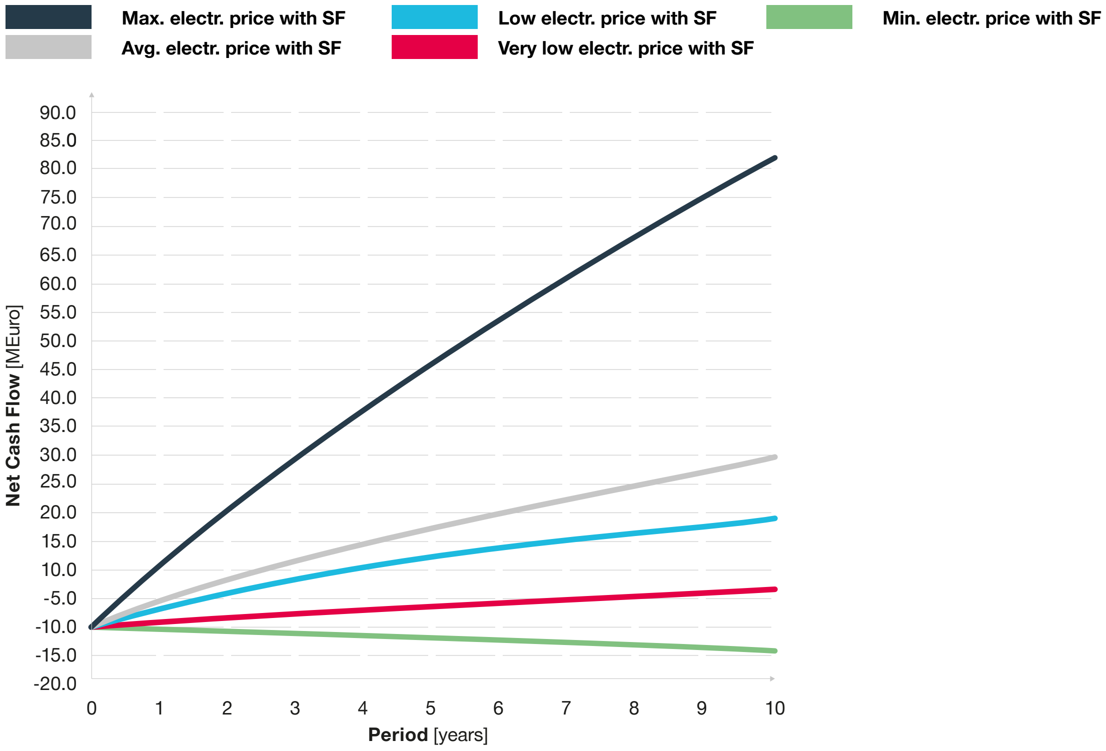


Figure 9: Influence of electricity price on the net cashflow over a period of 10 years for a CHP plant with supplementary firing

For the average European electricity price of 121 €/MWh the payback times for both CHP systems are quite short (around 2 years). The net present value, at nearly € 30 million for either solution, is considerable. The use of supplementary firing incurs additional investment costs and fuel consumption over the lifetime of the plant, but it provides more cost benefits relative to the case without supplementary firing.

Economic results for the average electricity price in Europe = 121 €/MWh

Solution type	Without supplementary firing	With supplementary firing
Net yearly savings [Million €]	4.69	5.05
Dynamic payback time [years]	1.8	2.0
Net present value over 10 years [Million €]	28.2	29.5

Table 4: Results of the economic evaluation of the CHP plants with average European electricity prices

Summary of the technical and economic study

The combined steam and power systems were evaluated with and without supplementary firing for energy consumption typical of the pulp and paper industry. The main technical and economic take-away points are:

- CHP plants are very efficient, flexible in operation and give the operator autonomy from the electricity grid.

- Because of their low CO, NO_x and CO_2 emissions compared to the conventional configuration, the CHP systems are very clean solutions.

- In case of higher steam demand, the utilization of supplementary firing makes the CHP solution even more efficient, with lower payback times and a higher net present value.

- At electricity prices of about 120 €/MWh, both assessed CHP solutions are economically attractive and profitable due to the short payback period of less than 3 years and the high net present value they offer. Unsatisfactory profitability would only be encountered in cases of very low electricity prices and high natural gas prices.

The benefits of the CHP solutions do not only depend on energy prices but also on how the CHP plant is operated, that is whether it is continuously or intermittently at full load or at part load. It is equally important whether a share of electrical power output is sold to the grid, or a small share of the electricity needed by the industrial process is purchased from the grid.

These different scenarios have an influence on the benefit generated by the CHP plant. For an individual assessment, a precise feasibility study requires a detailed profile of the electrical power and steam processes. In addition, some information about the relation between the steam and electrical power processes over the course of a typical year is required.

Figures

Tables

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