Superheated steam drying for paper production: process efficiency assessment

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Abstract:

Compared with hot air as drying medium, superheated steam has several advantages as drying agent, such as faster drying rates due to a higher overall heat transfer coefficient and lower viscosity allowing for better penetration of pores. It is already an established technology in drying processes in the food industry, as well as for biomass and pet food. In state-of-the-art paper production, the most energy intensive process step is drying with hot air. Using superheated steam for paper drying is an interesting alternative technology enabling more efficient heat recovery. This contribution presents different drying and heat recovery concepts, including air and steam drying as well as conventional energy supply by fossil fired boilers and heat pumps. It evaluates the potential reduction in final and primary energy consumption and CO_2 emissions based on process simulation in IPSEpro and compares the applicability of unused waste heat. Drying in steam atmosphere including steam compression for heat recovery was identified as the most beneficial concept. It allows for primary energy savings of 70% and CO_2 emission reductions of 88% compared to the benchmark concept with air drying.

Keywords:

Heat pumps; Heat recovery; Optimization; Paper drying; Process simulation.

1. Introduction

In the EU, the paper, pulp and printing industry consumed 1326 PJ or 13.7 % of the total final energy consumption in industry. Thus, it is the third largest final energy consumer after chemical and petrochemical industry (2121 PJ in 2020) and non-metallic minerals (1372 PJ). Most of the energy consumption is related to paper and paper products. To cover this demand, 30% of natural gas, 34% of renewables and biofuels and 21% of electricity are used. Minor shares are covered with other fossil fuels, such as oil or solid fuels. [1]

Typically, the type of produced goods in a paper mill has an impact on used energy carriers for energy supply. Factories producing both, pulp and paper, are often referred to as integrated factories. In comparison to factories producing only paper or board, in integrated factories a typical by-product is liquor from the chemical pulp production (cooking process) which is assessed as biogenous fuel. After pulp making, the used liquor is usually concentrated and burned afterwards in a liquor-boiler producing steam and in combination with a steam turbine also electricity. This leads to a high share of non-fossil energy supply for so called integrated factories.

However, other typical energy carriers for steam production in the pulp and paper sector, e.g., at sites using recycled fibres or (dry) pulp purchased from an external source, are natural gas, external waste streams, solid biomass, other biogenous residues or by-products from the production process such as internal waste streams, sludge or bark. Other possible, but less commonly used energy carriers are oil or coal. In order to provide energy in an efficient way, the following energy conversion technologies are often applied in those factories: steam turbines (often back pressure) in combination with gas turbines and / or different types of boilers, e.g. natural gas fired, but also using solids such as bark, sludge, coal or biomass as fuel. In general, the share of onsite electricity auto-production in the pulp and paper sector is rather high, usually realized with co-generation units. This is emphasized by an example from the Austrian pulp and paper sector. In 2021, 16000 GWh of energy were consumed, about 70% in the form of steam and 30% in the form of electricity. The on-site electricity production covered 65% of the electricity consumption. A total of 95% thereof was provided in co-generation units. [2]

 https://doi.org/10.52202/069564-0128

The 2050 Roadmap of the Forest Fibre Industry [3], which covers pulp and paper as well as wood-based products in Europe, outlines how to reduce CO_2 emissions to reach an 80% reduction by 2050. A large impact is achieved by substituting fossil fuels, more electricity-based installations using renewable energy and efficiency increase due to the application of BAT – best available technologies. However, without breakthrough technologies only a reduction of 50-60% CO_2 emissions is achievable. The aim of the breakthrough technologies is to lower the heat demand in paper making, by reducing water use and improving drying processes. Paper drying accounts for 70% of fossil energy consumption and is therefore an important field of action.

In state-of-the-art paper mills, paper is first dewatered mechanically in the press section followed by the drying section. Most commonly, multicylinder dryers are used [4]. Cylinder dryers consist of a series of cylinders that are heated on the inside by condensation of steam. The paper is moved around the cylinders and water is evaporated. Thus, humid exhaust gas is formed that leaves the hood of the dryer. The principle is shown in Figure 1. A recent technology review of paper drying by Stenström [4] showed that the multicylinder design has not undergone significant changes in the last 20 years. The most important new developments are impingement dryers using hot air that is blown onto the paper and the development of new steel cylinders for through air drying (TAD), as shown in Figure 2. In the analysis of Stenström [4], energy use is considered as very important with special focus on the recovery of humid exhaust air from the hood. However, there was no progress on new drying technologies, such as the use of superheated steam that has been studied in the past by several researchers. There are no industrial units installed so far.

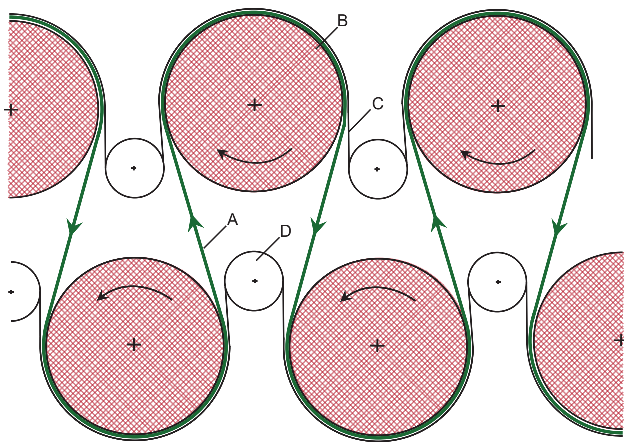

Figure 1. *Schematic visualization of steam heated cylinders in typical paper machines (A - paper, B - steam, C - felt, D - deflector roll)*

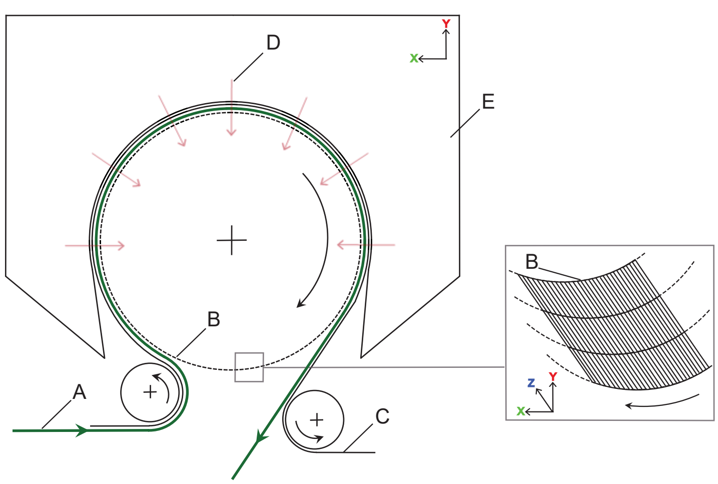

Figure 2. *Schematic visualization of Through-Air Drying (TAD) (A – TAD fabric, B – TAD cylinder, C – paper web, D – air flow, E – dryer hood)*

Superheated steam drying is already an established technology in the food industry, e.g. for distiller grains, beet pulp, rice, sea grass, dried fruit, potato products and tea, as well as for biomass and pet food. The main drivers to use superheated steam are an increase in product quality, less severe conditions for sensitive products and shorter duration of the drying process. [5-10] Recently an e-book [11] on superheated steam drying was published compiling the most important references in the field. The authors stated that activity was sporadic in the past, but it is now gaining momentum due to the potential energy savings.

In the field of paper production, superheated steam drying was studied experimentally by Kiiskinen et al. [12] in 2002 as steam drying offers many advantages, such as the potential to save energy and improve paper quality. It was a continuous steam dryer with a high velocity hood for steam impingement, that was operated with steam at 250°C. They studied paper quality, start up, the effect of non-condensable gases on heat transfer related to air intake and steam quality and impurities. It was found that steam drying offers advantages in terms of energy economy, if the exhaust steam can be used elsewhere in the process, e.g. in the drying cylinders, to heat the supply air in the dryer section, shower water, buildings, wire pits, paper web in the press section or in the calender, pulp, and to heat air or water in the power plant. The energy saving potential is 15-85% depending on the selected further use of the exhaust steam. Thus, heat recovery is based on cascaded use of steam provided in the conventional fossil fuel power plant.

This contribution presents different drying and heat recovery concepts, including air and steam drying as well as conventional energy supply by fossil fired boilers and heat pumps. It evaluates the potential reduction in energy consumption and CO_2 emissions based on process simulation in IPSEpro. The aim is identifying the most efficient process configuration as a contribution to the breakthrough technologies needed for efficient, decarbonized paper production.

2. Methodology

2.1. Process simulation in IPSEpro

The paper drying process, as well as the integration of heat recovery equipment, were investigated using the simulation software IPSEpro (Integrated Process Simulation Environment), which was developed for process simulations in the field of power plant and energy technology. It uses an equation-oriented solver for the calculation of mass and energy balances of steady state processes. [13]

The setup implemented as a flowsheet in IPSEpro corresponds to the actual process layout. The individual components of the process (unit operations such as the dryer, compressors, heat exchangers, etc.) are connected by streams that transfer mass and energy. The components are balanced according to conservation of mass and energy and the balances are strictly fulfilled for each component. The components can either be taken from the model library provided with the simulation software or they can be created by the user. Customized developed models for the dryer and the heat pump were used here.

Process data based on literature was used for the dryer model, which is explained in more detail in section 2.2. For the simulations, a simplified heat pump model was used. The model uses the temperature of the heat source and heat sink and the second law efficiency based on Carnot efficiency to calculate the power consumption, heat input and heat output of the heat pump. It is not necessary to specify the refrigerant or type of compressor in this model, so it can be used for potential assessment in a wide range of temperatures. The second law efficiency was chosen to be 0.45 based on the authors' experience.

2.2. Definition of benchmark process

A joint paper by the European Heat Pump Association (EHPA) and the Confederation of the European Paper Industries (Cepi) [14] published in 2023 is used to define the benchmark process of air drying for paper production as it summarizes the current status in the paper industry. According to [14], the dew point of the exhaust air is 60°C and typical steam pressures in the cylinders range from 1 to 9 bara. Typically, low pressures are used in the first cylinders and higher pressures in the last. Pressure levels are also influenced by paper grades and grammatures (max. 20%). It is found that 70% of steam use is below 6 bara and 50% below 5 bara in European paper mills, as it is illustrated in Figure 3.

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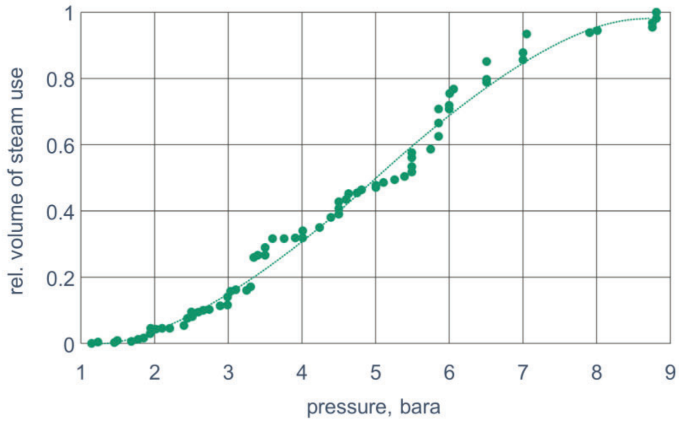

Figure 3. *Range of typical steam pressures in a paper machine, data from [14]*

In the benchmark process, 1 t/h of water is evaporated from the paper. When entering the drying section, the water in the paper has a temperature of 30°C. In the dryer, water is evaporated. For the sake of simplicity, only the enthalpy of evaporation for pure water is considered and enthalpy of sorption of water in the paper fibre structure is neglected. The enthalpy of evaporation amounts to 2257 kJ/kg for pure water at 1 bar. For example, enthalpy of sorption adds another 300 kJ/kg to reach 90% dry content and increases to 700 kJ/kg for 97-98% dry content [15]. In this evaluation, paper properties are kept constant for all concepts and are described by evaporation of 1 t/h. Thermal losses are neglected.

The steam cylinders in the dryer are supplied with saturated steam at 5 bara and 151.8°C. Steam is supplied from a combustion process operated with natural gas and a thermal efficiency of 90%.

Air is supplied from the production hall with a temperature of 30°C and is preheated with steam. The exhaust air from the dryer has a dew point of 60°C. It is assumed that it leaves the hood with 80°C followed by optional heat recovery using heat exchangers to preheat drying air. A total of 7454 kg/h of exhaust gas are formed when evaporating 1 t/h water from the paper. A pressure of 1 bar in the air system is assumed, pressure losses are neglected.

2.3. Environmental impact evaluation

Primary energy consumption:

Final energy is converted into primary energy using the primary energy factor f_{PE}. Primary energy also includes the production of the energy carrier itself, such as extraction, processing, storage, transport, conversion, transmission, and distribution to provide end energy. Primary energy consumption for electricity is predominantly influenced by the energy carriers and efficiencies used for electricity generation. For this comparison, factors based on current European averages are used. In 2019, the European Parliament defined the primary energy factor to be used for the calculation of the energy efficiency targets to 2.1 kWh/kWh for electricity [16], for natural gas, the factor amounts to 1.1 [17]

CO_2 emissions:

Like the primary energy consumption, CO_2 emissions are calculated based on the final energy demand and the emission factor f_{CO2} for CO_2-equivalent also considering other greenhouse gases such as methane or nitrous oxide. The emission factors f_{CO2} includes the production of the energy carrier itself, such as extraction, processing, storage, transport, conversion, transmission, and distribution to provide end energy. The CO_2 emissions from electricity are predominantly influenced by the energy carriers used for electricity generation. Currently, the use of electricity in the EU leads to 275 g_{CO2eq}/kWh [18], use of natural gas accounts for 268 g/kWh [19]. All factors are compiled in Table 1.

Table 1. Factors for the calculation of emissions, primary energy, and costs

	Unit	Electricity	Natural gas
CO_2 emissions factors (f_{co2})	g_{CO2eq}/kWh	275	268
Primary energy factors (f_{PE})	kWh/kWh	2.1	1.1

3. Results

3.1. Air drying

A1 is the benchmark process described above. Paper is dried in air atmosphere on drying cylinders that are supplied with steam at 5 bara (Figure 4). Steam is condensed in the cylinders at 151.8°C and the condensate returns to the boiler in a closed cycle. The boiler is operated on natural gas and has a thermal efficiency of 90%. In this process, 876 kW of natural gas are required. Exhaust gas at 80°C leaves the hood of the dryer containing the latent energy of the water evaporated from the paper. A total of 754 kW can be recovered if the exhaust gas is cooled to 20°C ($\dot{Q}_{Rmax}$), thereof 47 kW above the dew point temperature of 60°C.

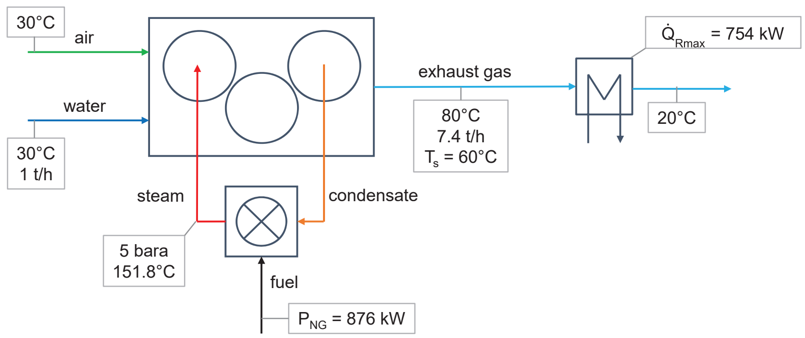

Figure 4. *Air drying with drying cylinders and steam from natural gas combustion (A1, benchmark)*

A2 accounts for heat recovery that is frequently implemented in paper mills (Figure 5). The exhaust gas is cooled to 55°C, a part of the heat is used to preheat the drying air to 65°C. Thereby, the natural gas demand is decreased to 805 kW. The remaining heat can be used for other sinks, such as preheating of water in other parts of the process.

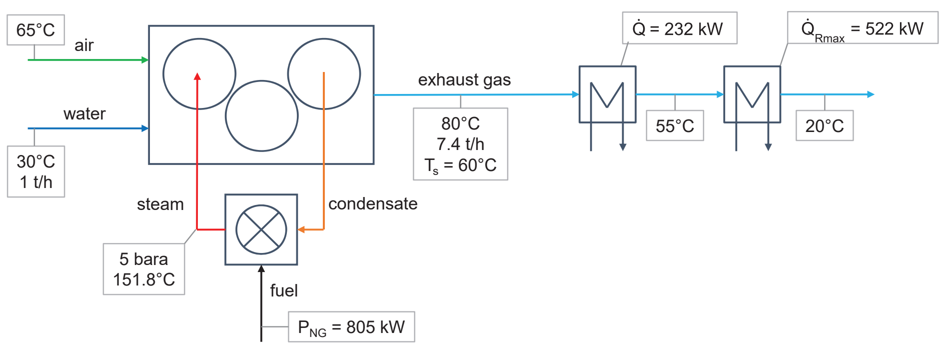

Figure 5. *Air drying with drying cylinders and steam from natural gas combustion and heat recovery (A2)*

In A3, heat from the exhaust gas is recovered with a heat pump (Figure 6). First, the exhaust gas is cooled to 38.7°C by an intermediate water cycle. The water cycle is the heat source of the heat pump, which is cooled by the evaporator of the heat pump. In the condenser, the heat pump produces saturated steam at a pressure of 1.05 bara (111°C) from the condensate of the cylinders. The steam is further compressed in steam compressors to 5 bara. In practise, a pressure difference of ca. 5 bar would require several compression stages with liquid injection to desuperheat the steam. About 5% of the steam are generated by injection for desuperheating. In the simulation, the setup is simplified to only one compressor with an isentropic efficiency of 70% without liquid injection.

In A3, the heat supply is fully electrified, the energy consumption amounts to 386 kW. The remaining heat recovery potential from the exhaust gas is 173 kW.

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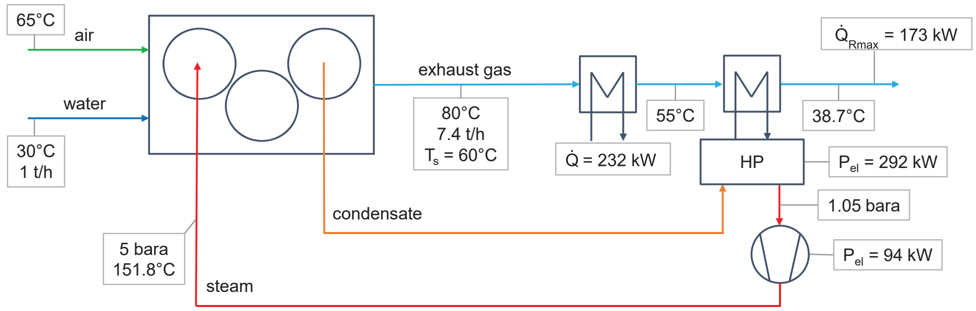

Figure 6. *Air drying with drying cylinders, heat recovery and heat pump (A3)*

In A4, there is no heat exchanger in the exhaust gas upstream of the heat pump (Figure 7). The exhaust gas is cooled by the intermediate water cycle that is the heat source of the heat pump. Thereby, the exhaust gas temperature after the heat pump is increased to 47.9°C. Due to the smaller temperature lift of the heat pump, it requires less energy. However, the drying air is preheated with steam in this concept, which increases the steam demand and the electricity consumption of the steam compressor. In total, 383 kW of electricity are needed. The remaining heat recovery potential from the exhaust gas is 333 kW.

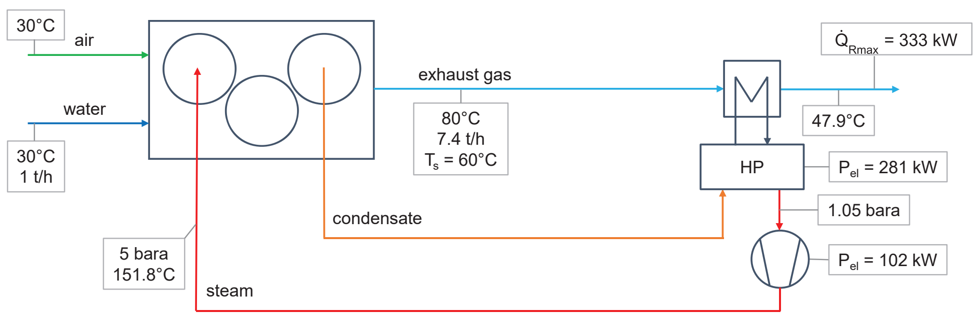

Figure 7. *Air drying with drying cylinders and heat pump (A4)*

3.2. Steam drying

In S1, the air atmosphere is changed to steam (Figure 8). Instead of drying air, superheated steam is supplied to the dryer with 151.8°C and a slight over-pressure of 1.05 bar to avoid air intake. To keep the inlet velocities constant, the drying steam volume flow is the same as the drying air flow in A1 (6261 m³/h). At the outlet of the dryer, the steam has a temperature of 111°C and has 10 K of superheat to avoid condensation on the paper. Water evaporated from the paper is present as excess steam which is discharged. The rest of the steam is reheated in the boiler and is recycled to the dryer.

Like A1, the cylinders are heated by another flow of saturated steam at 5 bara and 151.8°C. This stream is condensed in the cylinders and is reevaporated in the natural gas boiler. It is not in contact with the steam atmosphere.

In total, 794 kW of natural gas are needed. Heat recovery amounts to 726 kW if the excess steam is cooled to 20°C, whereas most of the heat occurs at the condensation temperature of 101°C.

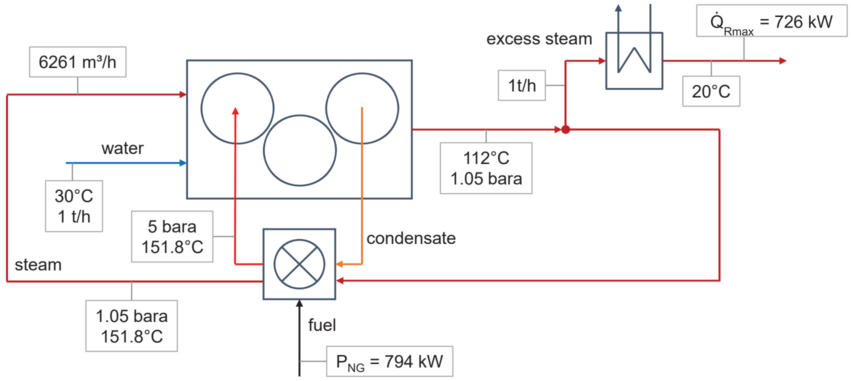

Figure 8. *Superheated steam drying with drying cylinders (S1)*

In S2, there are no cylinders, all energy for drying is supplied by steam like in impingement dryers or through-air-dryers (TAD). Thus, the heat distribution in the dryer is changed. However, there is no change in energy flows in this simple balance model (Figure 9). Natural gas demand amounts to 794 kW and the heat recovery potential to 726 kW as in S1.

The steam volume flow increases drastically by nine times to 59464 m³/h if steam is supplied at 151.8°C. If steam is supplied at 250°C, as it was in the lab test of Kiiskinen et al. [12], the volume flow is 21466 m³/h (3-fold increase compared to air drying). The increase in steam temperature lowers the volume flow of steam but has no relevant impact on the energy consumption of the natural gas boiler.

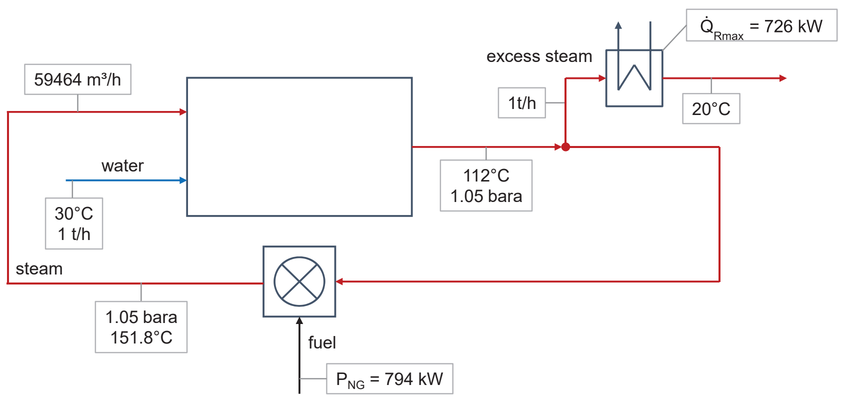

Figure 9. *Superheated steam drying without cylinders (S2)*

S3 is a fully electric concept with superheated steam drying and cylinders (Figure 10). After the dryer, a slip stream of 1 t/h of steam is separated. It is the mass flow originating from the water in the paper. It is compressed in a steam compressor to 5.4 bar, thereby the condensation temperature of steam increases to 155°C. The slip stream is condensed and transfers the heat to the second steam cycle in the cylinders. Then, the slip stream condensate heats the steam for the steam atmosphere to 145°C. As in S1, the steam volume flow for the steam atmosphere amounts to 6261 m³/h. After heating the steam atmosphere, the slip stream condensate still has a temperature of 149°C.

The steam compressor requires 139 kW of electricity. The heat recovery potential from the slip stream condensate is 151 kW.

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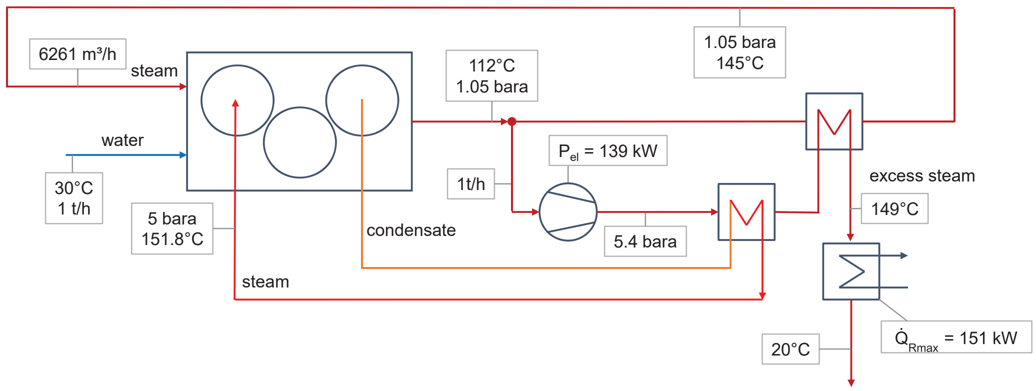

Figure 10. *Superheated steam drying with cylinders and steam compression (S3)*

S4 is another fully electric concept based on a heat pump (Figure 11). The slip stream (1 t/h) is the heat source for the heat pump and it is partly condensed. The heat pump produces steam from the condensate returning from the cylinders at 1.5 bara. The outlet pressure on the sink side of the heat pump was set to 1.5 bara to have a small temperature lift over the heat pump. The steam compressor further increases the pressure to 5 bara. A part of the superheat is used to reheat the steam for the steam atmosphere, then the steam is sent to the cylinders, where it is condensed. Energy consumption amounts to 154 kW. From the slip stream, 166 kW can be recovered, if it is further cooled to 20°C.

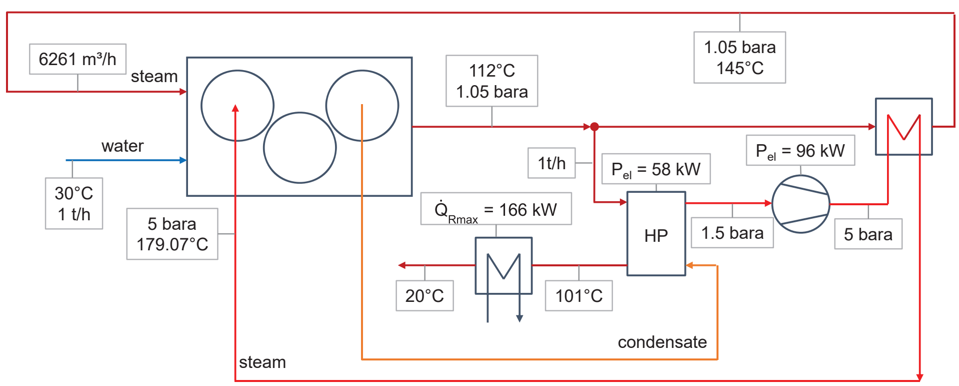

Figure 11. *Superheated steam drying with cylinders and a heat pump (S4)*

3.3. Discussion

Figure 12, Figure 13 and Figure 14 compare the concepts in terms of final energy consumption, CO_2 emissions and primary energy consumption. Final energy consumption decreases considerably for all concepts with heat pumps or steam compression (A3, A4, S3, S4), as they allow for recovery of the latent heat of the evaporated water from the paper. The same effect is found for CO_2 emissions. In terms of primary energy, the concepts A3, A4, S3 and S4 are still beneficial, but the difference to the concepts based on natural gas is smaller. The reason is the European primary energy factor, that is based on an electricity mix with less renewable energy than the one currently available in the EU.

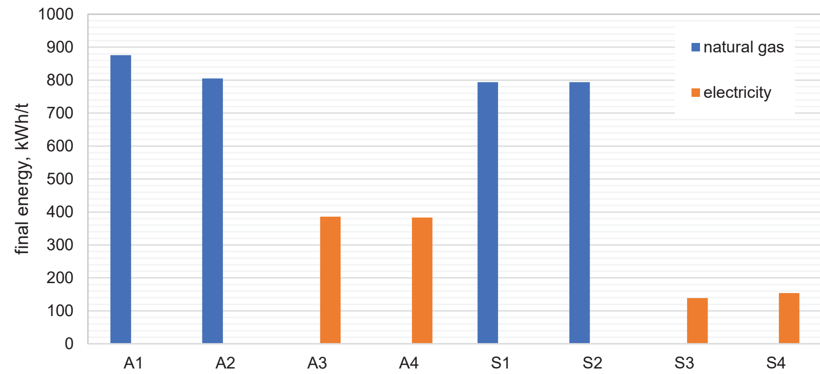

Figure 12. *Comparison of final energy consumption to evaporate 1 t/h water*

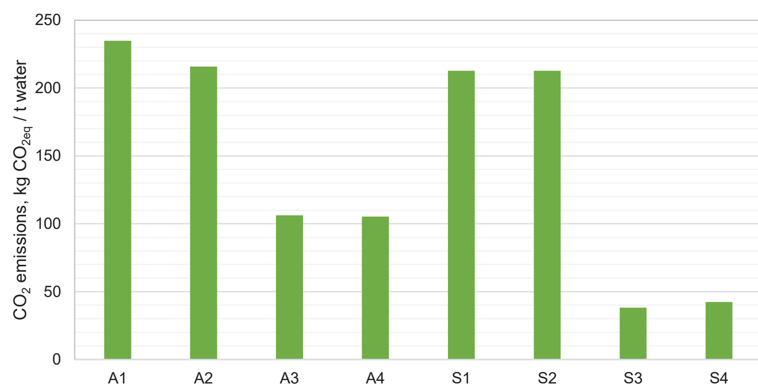

Figure 13*. Comparison of CO_2 emissions to evaporate 1 t/h water*

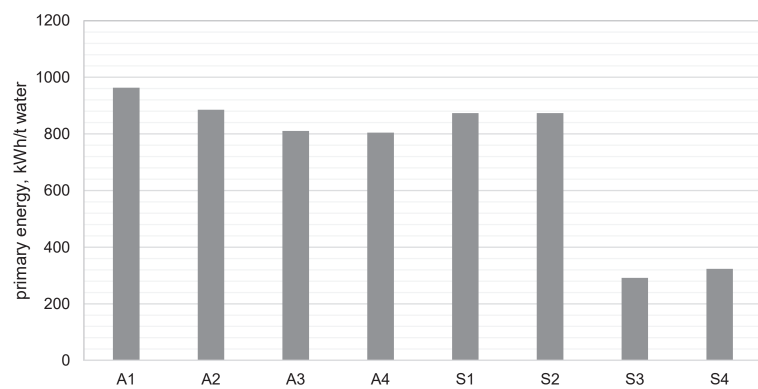

Figure 14. *Comparison of primary energy consumption to evaporate 1 t/h water*

The main difference between air and steam drying is that the dew point of the exhaust air is limiting heat recovery to low temperatures. A1 yields 754 kW, but mostly below 60°C. S1 and S2 yield 726 kW of excess steam that can be condensed at ca. 100°C. In the concept S3, the highest heat recovery temperature is available. Figure 15 visualises the heat recovery potential. The higher the temperature, the easier it is to find a suitable application. In A4, the heat pump is the only heat recovery measure. Compared to A3 (heat exchanger, then heat pump), more heat is available in A4 at a higher temperature. Energy consumption of A3 and A4 is in a comparable range. If there is no further heat demand at the paper mill, waste heat from steam drying can used for district heating, which is not possible for air drying.

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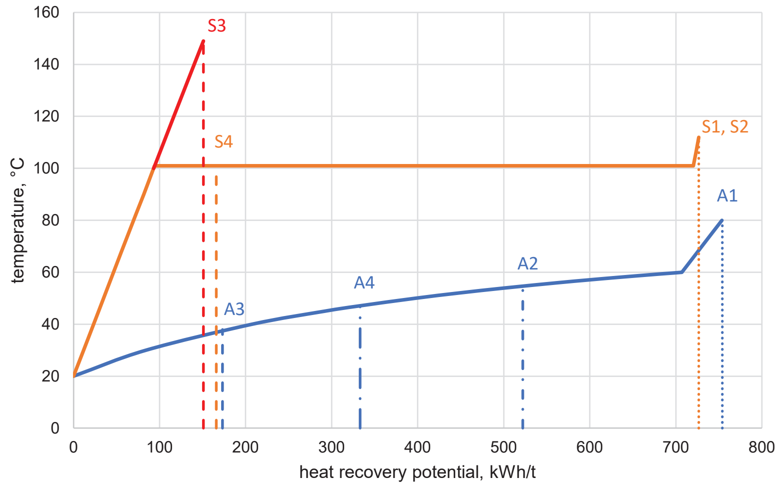

Figure 15. *Comparison of heat recovery potential for air and steam drying*

4. Conclusions and outlook

The most beneficial concept is S3 with steam atmosphere and steam compression for heat recovery. It reduces primary energy consumption by 70% and CO_2 emissions by 88% compared to A1, the benchmark concept with air drying. It also provides the highest excess steam temperature of 145°C that is well suited for further use.

The use of cylinders in the dryer is recommended to allow for low steam temperatures in the system. If the steam temperature is increased to 250°C, the volume flow is decreased. However, energy recovery with steam compression is more difficult, as the operation point moves closer to the boundaries of the operation envelope of steam compressors. The maximum allowable temperatures are typically at ca. 280°C, furthermore it must be considered that steam superheats strongly during compression.

To realize the concept S3, further research and demonstration is needed as an important part of the concept is that the steam for steam atmosphere is reheated and recycled. It has to be studied, what kind of impurities accumulate in the steam and how to remove them if necessary. Also, air intake should be avoided as it was already shown by Kiiskinen et al. [12]. In the simulation, a slight over-pressure of 1.05 bara was chosen for that reason. If the steam cannot be recycled, it can be condensed to evaporate clean steam. This would result in a more complex setup and in another temperature difference to overcome, which reduces the savings.

The simulation has shown that there is a huge potential in energy and emission savings if paper is dried in steam atmosphere using steam compression and condensation for heat recovery. Thereby drying is based on electricity only. The concept S3 is a suitable breakthrough technology to considerably improve paper drying.

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