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Energy integration and electrification opportunities in industrial laundries

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Abstract:

The industry and service sectors in Europe rely on fossil fuels to provide process heat, while a lot of low temperature energy is rejected to the environment. Energy efficiency measures reduce energy use and recover some of the excess heat, but a full decarbonisation requires the shift to renewable energy. The share of renewable energy in the electricity mix is steadily increasing. The electrification of industrial processes will thus be important for decarbonisation. Industrial laundries are energy intense sites where large quantities of garment are washed, dried, steamed and ironed. While new detergents allowed for a reduction in temperature in the washing process, other processes still take place at temperatures above 150 °C. In many laundries, the heat to the processes is provided from a central natural gas boiler. The humid air from dryers, steamers and ironers is often emitted to the environment without heat recovery. Utilizing this excess heat and electrifying the whole heating demand of the processes has the potential to reduce both the energy use and environmental impact. In this work an analysis of processes in an industrial laundry was conducted to establish the process heating demands and excess heat sources. Based on this analysis, strategies for electrifying the whole site were developed with heat pumps being a central element for an efficient conversion. These strategies are based on an energy integration analysis considering the time profiles for each heating and cooling demand. The study showed the feasibility of electrifying industrial laundries. The wide implementation of heat pumps in the processes allowed for a reduction in primary energy use by up to 50 % and cost-effective electrification in some scenarios.

Keywords:

Electrification, Decarbonization, Dryer, Heat pump, Industry, Laundry, Process Heat.

1. Introduction

The use of fossil fuels for supplying heat to industrial processes is becoming unattractive from economic perspectives in some countries due to increasing energy taxes and should be terminated from an environmental point of view. The implementation of energy efficiency measures, utilisation of excess heat and use of electricity from renewable sources for process heat supply are important elements in the decarbonisation of the industry and service sectors. The benefits of electrifying industrial processes can be manifold, such as reduction in final energy use, improved product quality and increased production output [1]. There are further a number of technologies available for electrification, ranging from electric boilers, heat pumps and resistance heaters to infrared, microwave and electron beam heating [2]. The number of industrial processes that can be converted to electricity is further high [1] and would allow for a high potential reduction in fuel related CO_2-emission reductions [3].

Recent research has shown that high-temperature heat pumps [4] and a large-scale implementation of heat pumps in production sites [5] can be a cost effective way to electrify industrial processes. A bottom-up methodology for assessing the electrification potentials of industrial processes was presented in [6]. Policy instruments for the deep-decarbonisation of the energy intensive industrial industry are given in [7]. The power to heat potential in the German industry was established by Gruber et al. [2].

The shift from fossil fuels to electricity in the industry is important in reaching the GHG emission targets. For many processes, such as in the cement or chemical material manufacturing, research is required to find new processes and alternative products which can be manufactured completely without use of fossil fuels or without emission of process-related CO_2 emissions. In other industries, where only heating and cooling of product streams is required, the conversion can technically be achieved today. Such industries requiring only heating and cooling are for instance found in the food and service industry. In this paper the case study of a laundry is used to investigate the economic feasibility of electrifying the laundry and which technical solutions are most suitable. It is further analysed how the process of electrification can look like and how it can be adopted to a specific industry.

A few studies have analysed the energy use and energy efficiency in industrial laundries. Bobák et al. [8] created an energy use model of industrial laundry systems. Bobák et al. [9] further analysed options for heat recovery and summarising challenges in their implementation. A case study for a tunnel finisher (steamer) is further given. Máša et al. [10] analyzed the energy and water use for processing of two garment types and suggests energy efficiency measures and performs economic analyses. Kuba et al. [11] described the acquisition of data in industrial laundry facilities, including different levels of data sources and suggestions of topologies and flows in data management systems. Several studies focus on modelling and energy efficiency of tumbler drying in laundries [12]–[14].

2. Method

2.1 Case study and process description

The overall process of the laundry is shown in Figure 1. The fabrics (e.g. linen, clothes, and towels) enter a Continuous Tunnel Washer (CTW), where the material is washed. After the washing, the fabrics are mechanically dewatered in either a press or centrifuge. The water is reused in the CTW and the fabric enters a tumble dryer. Depending on the type of fabric, it is either fully or partially dried. Afterwards, clothes enter a tunnel finisher, linen a roll ironer and towels directly leave the production line [15]. The described process is typical for larger industrial laundries processing e.g. hospital or hotel fabrics. The case study is based on an industrial laundry in Denmark for which the necessary data was collected onsite. Process parameters can vary based on the equipment used and type of fabric. In this conference paper the focus is placed on the CTW and tunnel finisher.

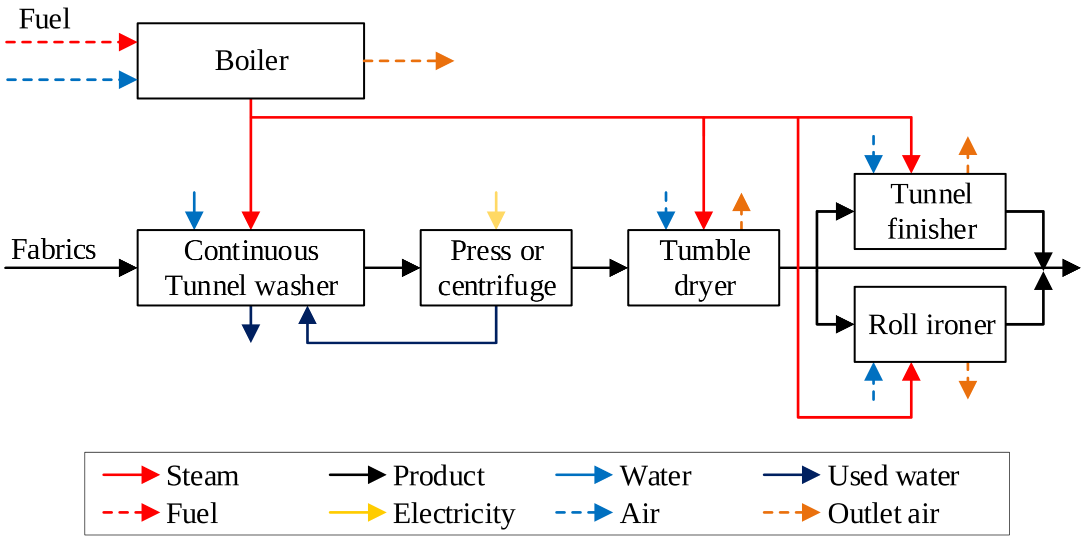


Fig. 1: Process description of the industrial laundry.

The process heat is supplied with steam at 9 bar and a saturation temperature of 180 °C by a central natural gas-fired boiler. Wastewater from the CTW is drained and air from the dryer, tunnel finisher and roll ironer are removed through individual stacks.

2.1.1 Continuous tunnel washer (CTW)

The CTW typically have three zones consisting of up to 13 compartments and operate in counter flow, meaning freshwater is added in the last compartments, from where it moves forward in the opposite direction of the fabrics. This process is schematically shown in Fig. 2, where the three main zones are included. In the first zone reused water extracted from the press is used to soak the dirty fabrics. In this zone also chemicals are added. In the second zone (compartments 2 to 7) the washing takes place. In the current system, steam is injected in these compartments to reach a washing temperature of 60 °C and reused rinse water is used to wash. In the last compartment the clean fabrics are rinsed with fresh water. Rinse water and water extracted in the press or centrifuge is reused. The water from washing is however discarded.

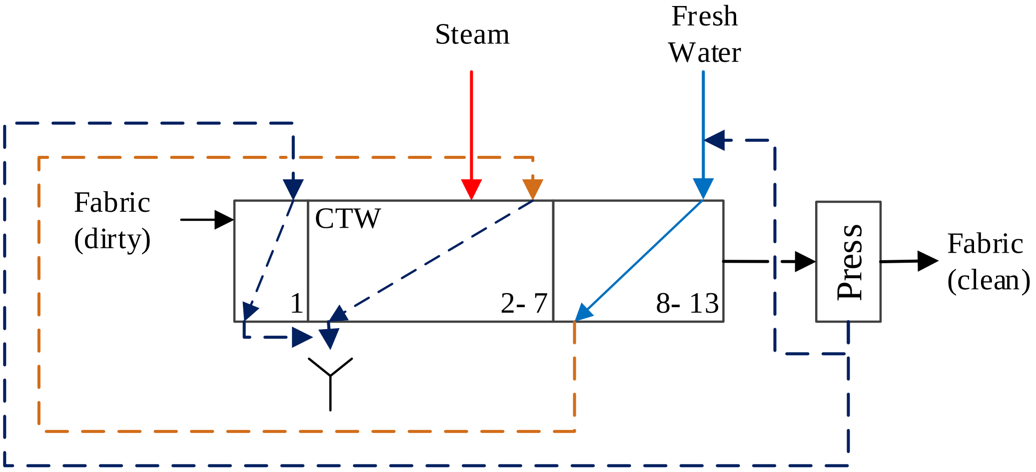


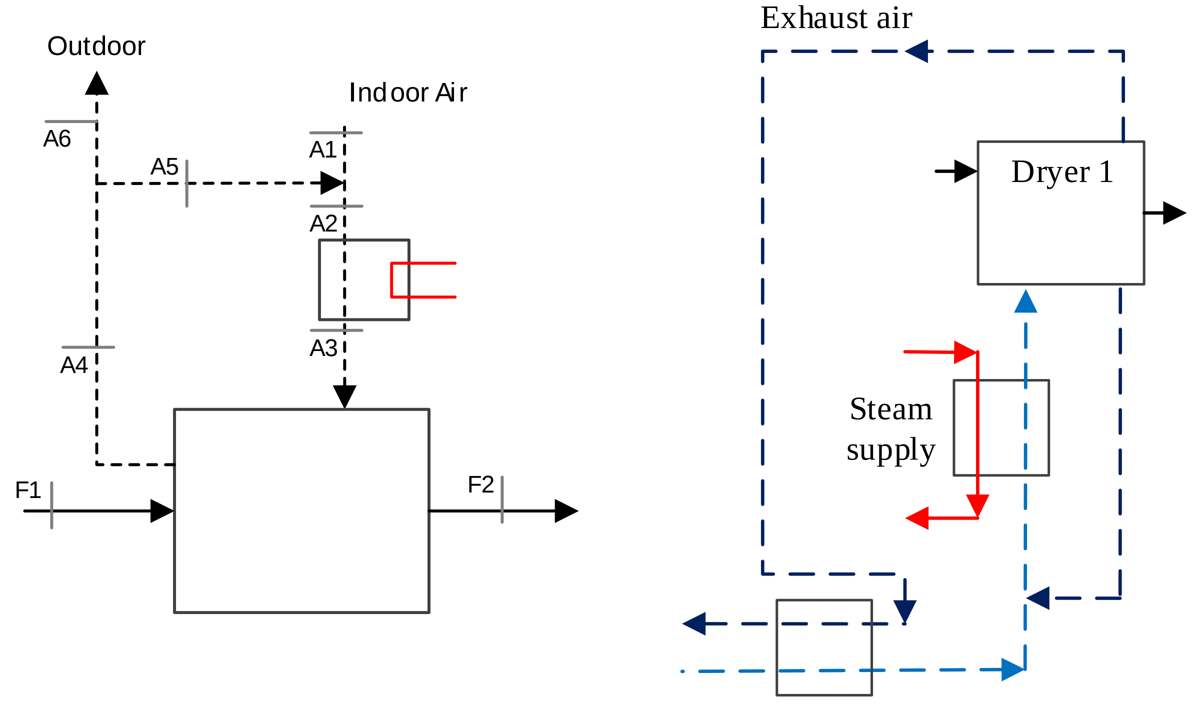
Fig. 2: Process description of the continuous tunnel washer (CTW).

2.1.2 Tumble dryer (TD)

The tumble dryers have various drying programs, ranging from short 4-minute cycles (if the material is afterwards put in roller or steamer) to 20 minutes for full drying. The 20 minutes cycle includes a cool down cycle with fresh air. The outlet air temperature reaches for short cycles up to 80 °C and 120 °C for long cycles. In Fig. 3 (a) the schematic model of the current dryer is shown. The wet fabrics enter at F1 and leave the dryer at F2. Indoor air is sucked in at A1 and mixed with recirculated air A5. The air is heated with steam and enters the dryer at A3.

2.1.3 Tunnel finisher (TF)

The tunnel finisher is used to flatten and dry work clothes. They consist of four zones, where (i) the clothes are heated with hot air, (ii) are flatten in a humid air zone where steam is sprayed in, (iii) are dried in another hot air zone and at the end (iv) pass a cool down zone. The hot air is either heated by steam or a natural gas burner to temperatures of up to 145 °C. The outlet temperature of the air is between 90 °C and 100 °C.



(a) *(b)*

Fig. 3. Schematic of the mass and energy flows of the tumble dryer with air recirculation (left) and with air recirculation and heat recovery (right)

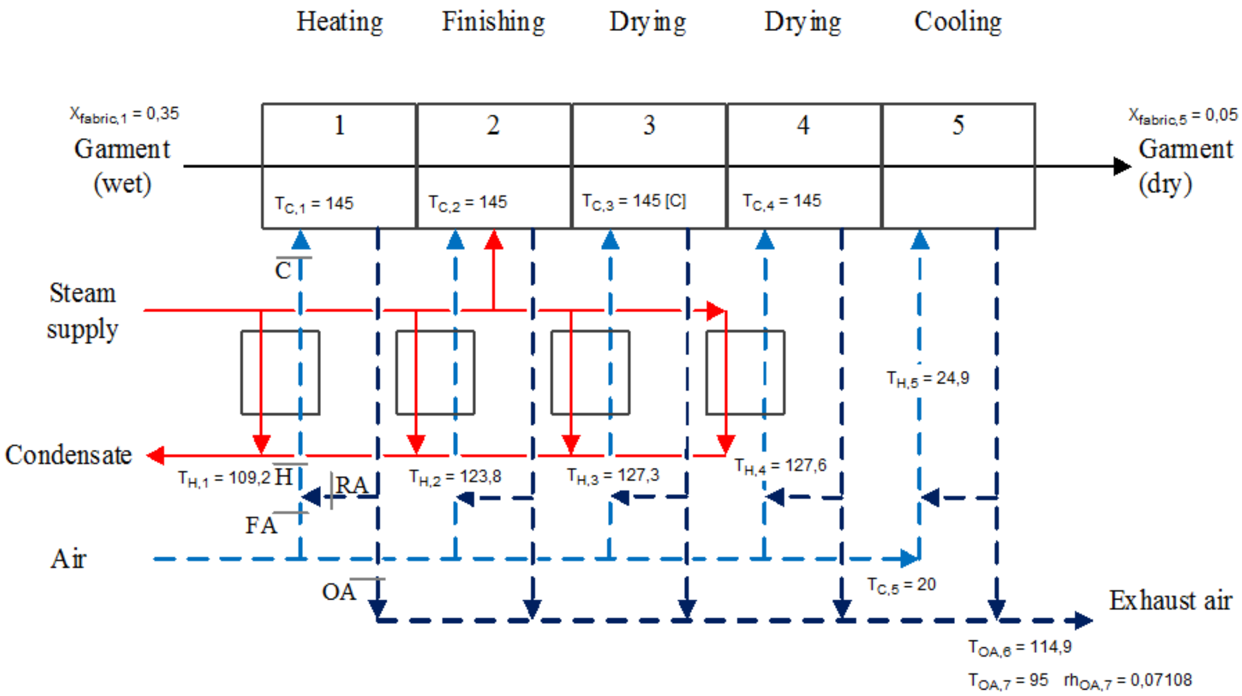


Fig. 4. Schematic of the tunnel finisher with the main temperature set-points (T) in °C, water content of the fabric (X) in kg/kg and relative humidity of the air (rh).

2.1.4 Roll Ironer (RI)

The roll ironer irons fabrics, such as bed sheets and towels, which enter the ironer humid. The fabrics pass several cylinders which press the fabric on a mould. The mould is usually steam heated and the evaporated water from the fabric is sucked into the cylinder which is perforated. The hot and humid air is sucked away and discharged to the environment.

2.2 Electrification strategies

In this work two main electrification strategies were investigated which were combined with energy efficiency measures. The first approach consists of an electricity-based central utility system, while the second approach corresponds to a decentralized integration of electrification measures. The strategies are based on approaches developed in [5].

The central approach shown in Fig. 6 electrifies the process heat supply through a central heat pump which delivers steam. The source of the heat pump is the combined exhaust air flow from the components. This humid air has a high energy content. Through condensation of the water it can supply a substantial part of the heat supply for the heat pump. The advantage of this approach is the possibility to operate the components without major modification. The central heat pump can further be installed in the old boiler house and fluctuations from the batch processing (i.e. dryers) are balanced out or can be through installation of buffer tanks.

The decentral electrification approach shown in Fig. 6 aims at optimising each process step individually though direct heat recovery and heat pump integration. The advantage is that the supply temperatures can be adjusted to the actual process requirements in each component. Further it is possible to electrify the most cost-efficient solutions first. The heat pump for the CTW supplies for instance heated fresh water and heats water in the other washing chambers (double arrow).

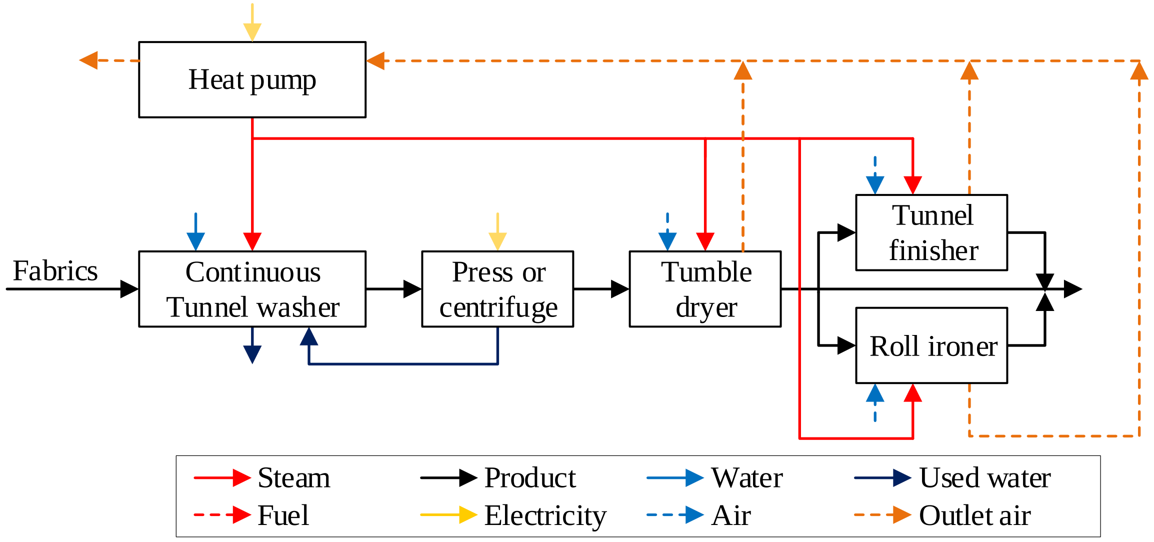


Fig. 5. Central electrification strategy of the laundry based on central steam generating heat pump.

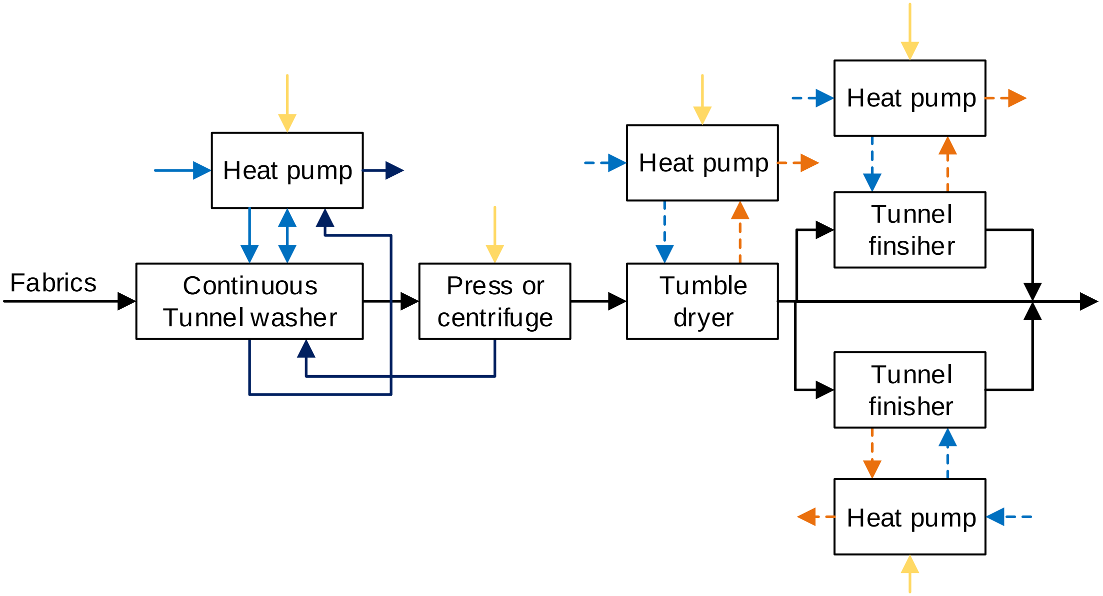


Fig. 6. Decentral electrification strategy of the laundry.

2.2.1 Heat pump modelling

Both the central and the decentral electrification scenarios considered heat pump-based process heat supply. Depending on the specific application and the respective boundary conditions, different heat pump technologies were considered.

In the decentral scenario, single vapor compression heat pumps with hydrocarbons were considered. In some cases the cycles comprised an internal heat exchanger that subcooled the refrigerant before expansion and superheated the suction gas before compression. At a supply temperature of up to 120 °C, n-butane (R600a) was considered as working fluid, while isopentane (R601a) was considered at higher supply temperatures. In applications with a too large temperature lift, a cascade arrangement of these two technologies was considered. In both cycles, a minimum superheating of 5 K was maintained at both the inlet and the outlet of the compression.

The cycle simulations were based on steady state models, consisting of energy, mass and impulse balances. The compression processes were modelled with an isentropic efficiency of 75 %. No heat loss from the compressors was considered. The heat exchange processes were determined by a minimum temperature difference throughout all heat exchangers of 5 K, which indirectly determined the heat exchanger sizes. The refrigerant was subcooled to this pinch point temperature difference before being further subcooled in the internal heat exchanger. The modelling approaches correspond to the models as presented in [5], [16].

In the central scenario, a cascade heat pump system as shown in Fig. 7 was considered, while the previously introduced hydrocarbon systems were considered as the bottom heat pumps. The top cycle was a multi-stage steam compression cycle using turbo compressors as presented in [4], [17], [18]. The bottom heat pumps evaporated steam from a central evaporator. This was subsequently compressed in multiple stages. After each compression stage, the steam was desuperheated to 10 K above the saturation temperature by liquid injection. The suction gas of the first compression stage was superheated by 10 K by recirculating the compressed gas. The number of compression stages and the compression ratio was optimized according to the specific application. The condensate was assumed to be returned at the temperature of the central evaporator.

2.2.2 Economic evaluation

The economic evaluation of the solutions is based on the estimation of investment costs, the definition of operating costs and evaluating the investment. First the bare module costs were estimated based on cost correlations found in the literature [19]–[21] and data provided by suppliers. These bare module costs of the equipment accounted for pressure and material factors and were adjusted using the Chemical Engineering Plant Cost Index (CEPCI) for the year 2017. The obtained bare module costs were multiplied with a factor of 1.18 to account for contingency and fees and an additional 15% of the total module capital costs were added to obtain the total capital investment costs (TCI) of the equipment.

The energy prices of natural gas and electricity were determined for Denmark based on [22], [23] and for Germany based on [24]. For the case of Denmark, the energy price forecasts were adjusted based on the expected taxes for energy use in industrial processes and for the case of natural gas with CO_2-emission costs. Maintenance costs were further included as a one-time payment of 20 % of the total capital investment costs [21]. The maintenance costs of the existing system were not included, which means that maintenance is an additional expense for the electricity-based systems.

The economic evaluation was based on several indicators to assess the feasibility and profitability of investments. The Net Present Value (NPV) was used as an indicator where a lifetime of 20 years, a discount rate of 5 % and an inflation rate of 2 % were applied.

3. Results

3.1. Central electrification

In the central electrification solution, all exhaust air streams are collected and mixed as shown in the previous figures. In the case study this leads to an exhaust air stream at 82 °C and a humidity ratio of 0.061 kg/kg. This stream is cooled serially in the two heat pumps. The first heat pump (B-HP1) cooled the air stream to its condensation temperature of 22.8 °C before it was further cooled in the second heat pump (B-HP2) while the condensing heat was recovered. The heat was supplied to the central evaporator, which operated at 100 °C. From the central evaporator, the steam was compressed in two stages with a compression ratio of 2.5 and 2.8 respectively. The steam was supplied at 180 °C, with the condensate being returned at 120 °C. This leads to a total COP of 1.87, with an electricity use of 1.285 MW. The evaporation temperature was 110 °C, and the pressure after the first TC was 3.6 bar and 10 bar after the second one.

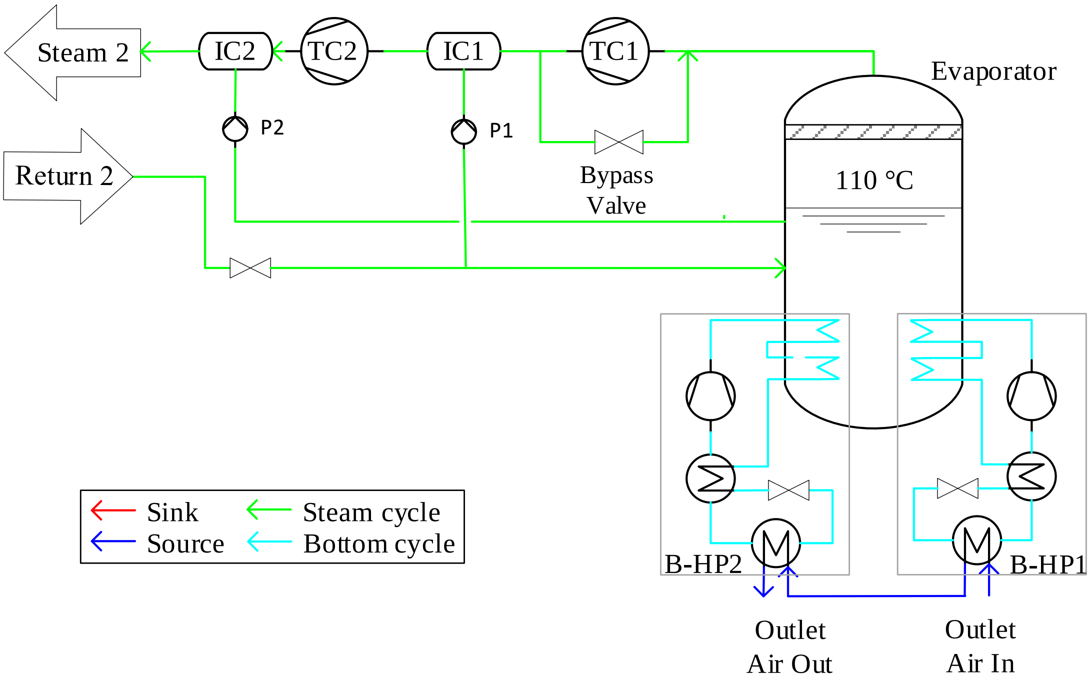


Fig. 7. Steam generation heat pump in multistage cascade system.

3.2. Decentral electrification

For each of the elements of the industrial laundry a solution for electrification was developed which used a heat pump and if possible direct waste heat recovery. The electrification concept for the CTW is shown in Fig. 8. To replace the heat in the washing section, previously added through steam injection, a system for recovering the heat in the wastewater was analysed. The rinse water from the rinse section is heated with a heat pump, which cools down the wastewater. To reach a temperature of 65 °C the rinse water is further heated electrically. The hot water is then added to the washing section. To maintain the minimum washing temperature of 60 °C, a heat exchanger is used to heat the washing water with water from the high temperature water tank. The single stage heat pump in this system reaches a COP of 4.1 and reduces the energy use per mass of fabric from 130.8 kWh/t to 33.6 kWh/t.

The tunnel finisher was electrified using a high-temperature heat pump, generating steam to be used in the existing system (see Fig. 9). An alternative solution preheating the air through a heat pump and generating steam with an electric boiler was further analyzed but omitted from this work due to a limited economic performance. Therefore, only the high-temperature heat pump was considered in this work. The two-stage heat pump had a COP of 1.94 and reduced energy use per mass of fabric processed from 0.668 kWh/kg of natural gas to 0.327 kWh/kg of electricity.

For the dryer and roll ironer similar solutions based on high-temperature heat pumps were implemented. However, here a single stage HP with internal heat exchanger was used. For the tumble dryer the operation of 6 dryers was considered to balance out the batch nature of the process and to obtain an accumulated steady consumption of all dryers. The COP for such a heat pump was 1.67 and reduced the product specific energy use from 0.609 kWh/kg to 0.345 kWh/kg. Due to higher air outlet temperatures in the roll ironer a COP of 2.15 was obtained. The electricity use was 0.220 kWh/kg and reduced from the initial natural gas consumption of 0.473 kWh/kg.

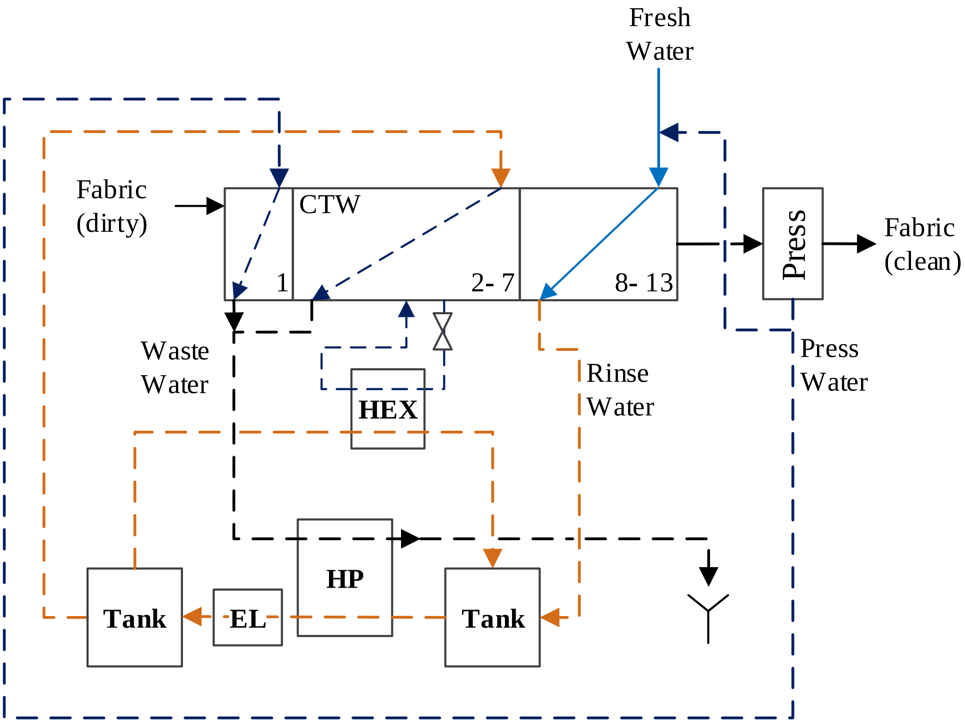


Fig. 8: Electrification of the CTW with waste heat recovery.

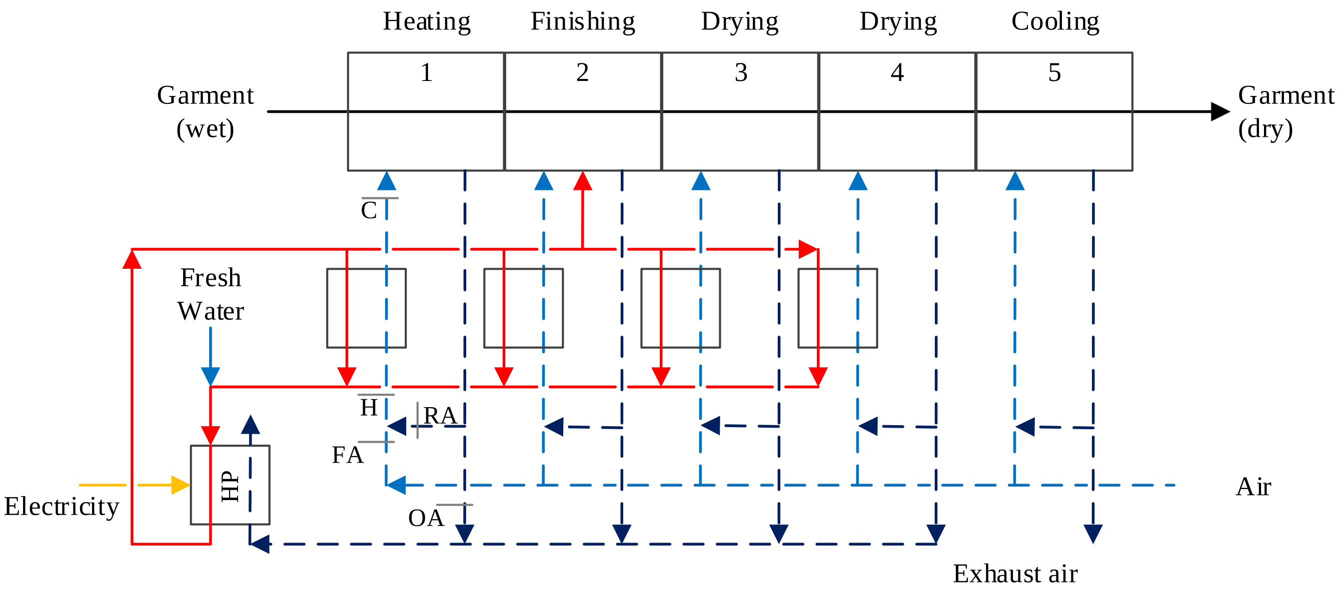


Fig. 9: Electrification of the tunnel finisher with waste heat recovery.

3.3. Comparison of solutions

In Fig. 10 a comparison of the energy use for the two electrification strategies and the existing systems (BAU) steam and natural gas use is shown. The difference between BAU Steam and BAU boiler are the heat losses through the flue gas. Both, the central and decentral HPs, reduce the energy use by around a factor two compared to the natural gas consumption of the existing boiler. In the decentral electrification the tumble dryers account for the highest share in electricity use. The CTW only has a minor contribution.

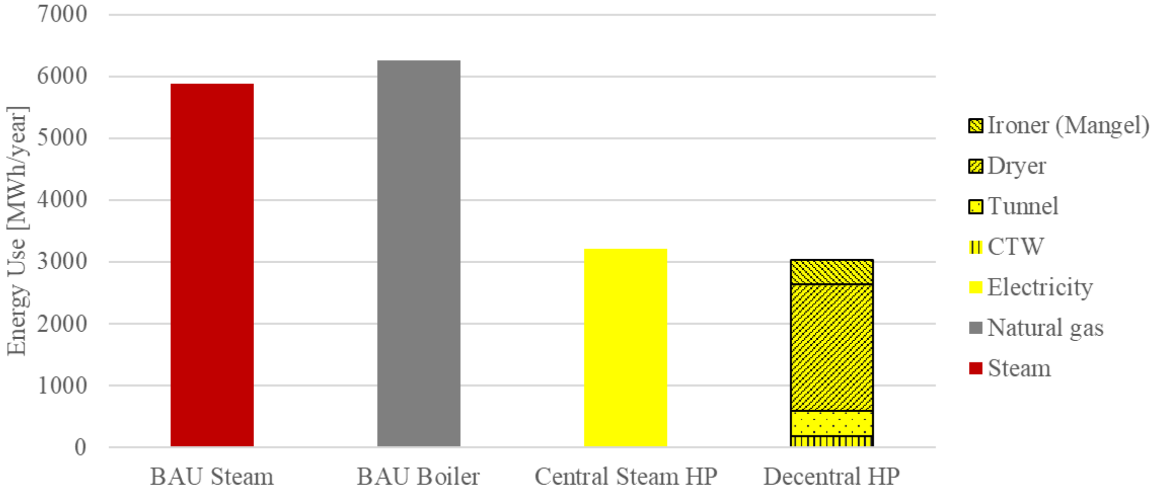


Fig. 10: Summary of the energy use before electrification (BAU) and after electrification for the central and decentral solution.

3.4. Economic evaluation

In Table 1 the investment costs are shown. The central electrification requires investments of around half a million Euro more than the decentral electrification solution. This is despite larger components used in the central heat pump, which are often cheaper because of economy of scale. The better sizing in terms of temperature requirements of the heat pumps allows to reduce the costs in the decentral solution.

Table 1. Overview of total and specific investment costs for each of the electrification strategies.

		Investment	*Total Investment [1000'€]*	*Specific Investment [€/kW$_{electrified}$]*
Central Electrification				
	Utility	Central Steam HP	2,357	2,216
Decentral Electrification				
	CTW	WHR + HP	181	786
	Tunnel Finisher	Steam HP	422	2,454
	Tumble Dryer	Steam HP	912	1,671
	Roll Ironer	Steam HP	343	1,856

In Fig. 11 the Net present Value (NPV) for the electrification strategies is shown. In addition to solutions only considering WHR in the TD and TF are included. The NPV was found for constant fuel prices based on expected values for the years 2017, 2020, 2025 and 2030. Further the energy prices for Denmark and Germany were used. It can be seen that all electrification solutions, except the investment in electrifying the CTW would yield a negative NPV over the lifetime. While in Denmark the future energy prices point into more favourable conditions for electrification, this is not the case for Germany with the used price forecasts. Investing only into WHR in the tumble dryer (TD-WHR) would also be an attractive investment for the laundry.

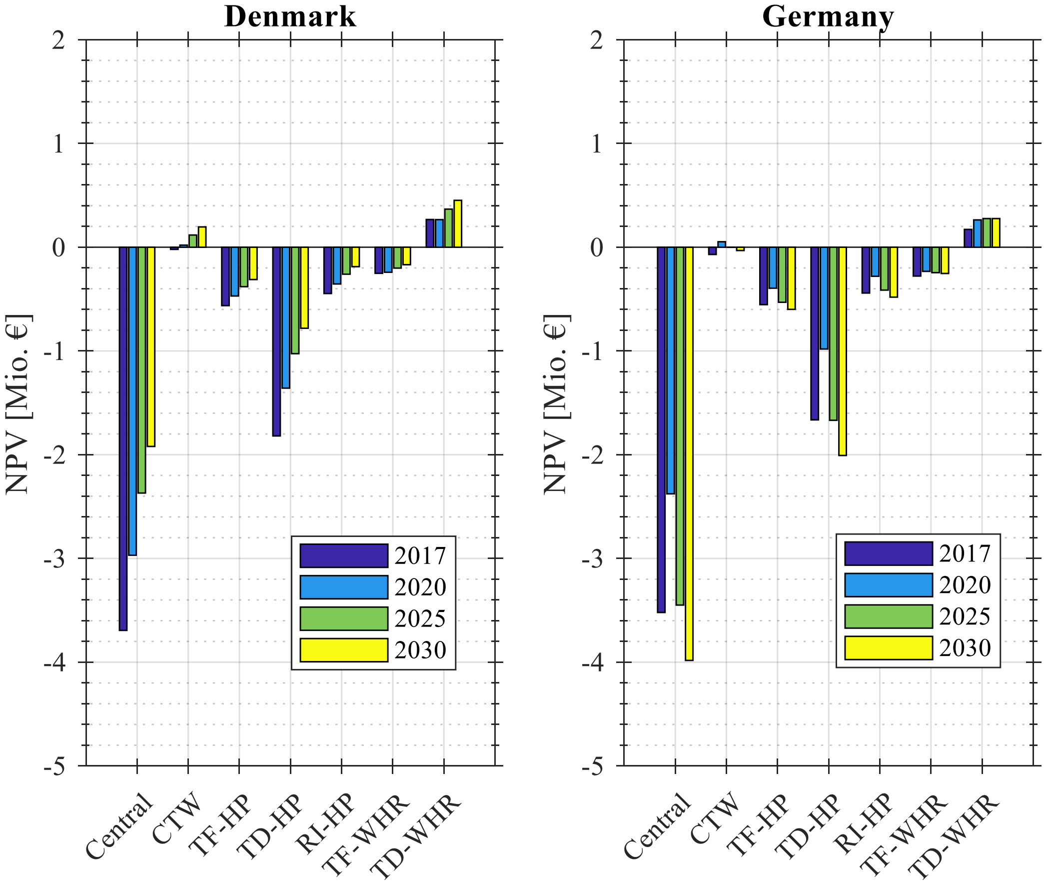


Fig. 11: Net Present Value for investments in central electrification (Central), the decentral electrification (CTW-Continuous Tunnel Waster, TF- Tunnel Finisher, TD – Tumble Dryer and RI – Roll Ironer) and alternative waste heat recovery (WHR) for the TF and TD without electrification.

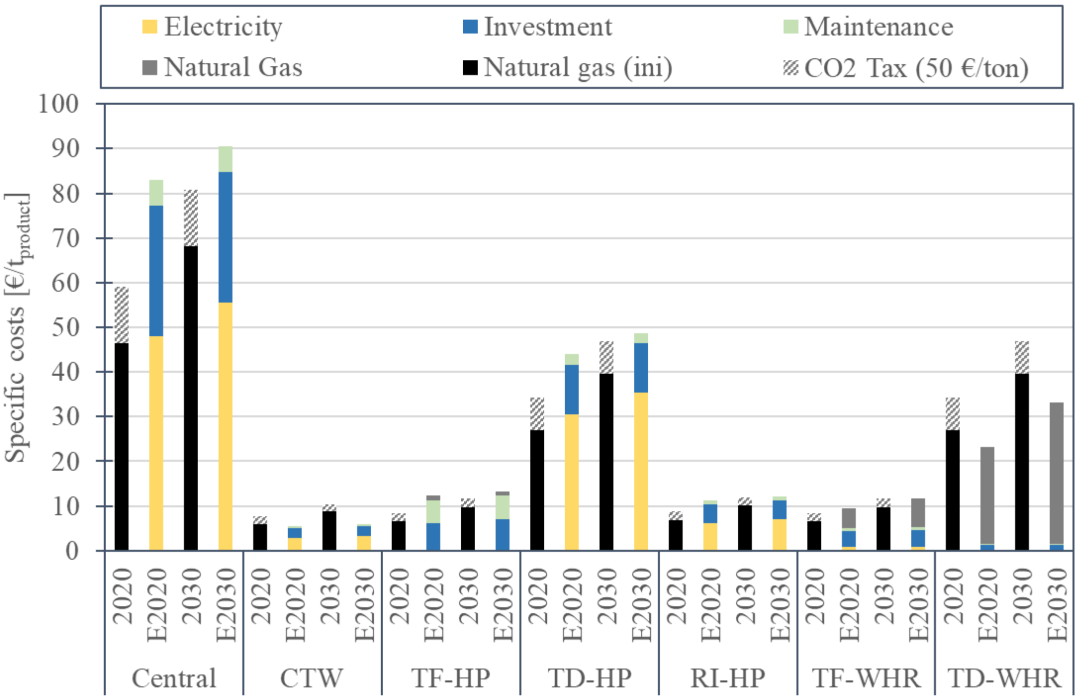


Fig. 12: Specific energy related costs in the years 2020 and 2030 without and with electrification (E) for the different investment opportunities.

The specific costs for processing one ton of fabrics are shown in Fig. 12 for a business as usual (BAU) case in 2020 and 2030 and an electrification case (E2020 and E2030). The specific costs are divided into the parts related to energy (natural gas or electricity), investment, O&M and a theoretical CO_2 tax of 50 €/ton as shown. It can be seen that despite the CO_2 tax, the specific production costs are higher for the central electrification than keeping the system as it is. For the decentral solutions the CTW and roll ironer (RI) have lower specific costs in E2030 than when keeping the system as it is. The TF and TD also come closer to a break-even point in 2030 with the CO_2 tax. It has to be considered that additional investments and maintenance of the natural gas boiler were not included. It can be further noted that the costs for energy are even without taxes very close to each other. Increases in natural gas prices, are therefore likely to increase the profitability to shifting towards electricity.

4. Discussion

In this work it was shown how the heat supply of processes in an industrial laundry can be converted from natural gas to electricity using heat pumps and waste heat recovery. Some aspects of optimisation leading to a reduced energy use and increased electrification were not considered, as they would require detailed analysis of the process itself. For example, an increased use of chemicals or more mechanical work (see Sinner's diagram [25]) in the CTW could reduce the washing temperatures further. Such solutions require rethinking and new designs of the processes but can lead to new electrification opportunities.

In this case study, the economic analysis showed that if including investment under the given conditions, the electrification solutions in almost all scenarios are economically infeasible. But if investment in new boilers is required it would make the electrification solutions more profitable. Some costs, e.g. maintenance of the natural gas boiler and its replacement at the end-of-life were not included. These costs would make the electrification solutions more profitable and a higher CO_2-tax would have further a high impact on the outcome of the analysis.

5. Conclusion

In this paper two solutions for electrifying an industrial laundry were modelled, analysed and compared. Electrification was defined as replacing a fossil fuel-based heat supply with electricity as the source for heating. The first solution was a central electrification of the system through a heat pump generating steam using the humid exhaust air of the processes as the heat source. The second solution electrified each process individually, meaning an electric solution based on heat pumps was developed for the continuous tunnel washer, tunnel finisher, tumble dryer and roll ironer. It was shown that electrification reduces the final energy use of the laundry by a factor two in both solutions, as waste heat is recovered through heat pumps. The central solution requires higher investment costs but allows for operating the processes in a similar way as with a natural gas-fired boiler. The decentral electrification is slightly cheaper in investment costs in this case study and has the additional advantage of allowing the conversion of the processes to start with the most cost-effective one. However, the economic analysis showed that both solutions are not economically feasible with the chosen conditions in Denmark and Germany and fuel prices estimated until 2030. This was, however, based on several assumptions involving uncertainty and the operating costs was not much higher. Furthermore, it may change if higher CO_2-taxes are introduced.

Acknowledgments

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