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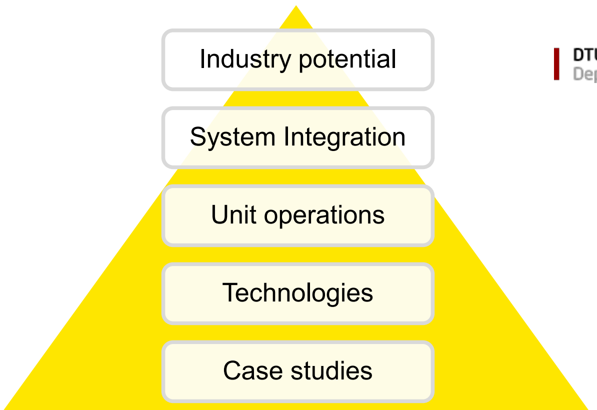
Electrification of processes and technologies for Danish Industry

Elforsk project 350-038

Appendix C



DTU Mechanical Engineering
Department of Mechanical Engineering
viegand maagøe energy people
DANISH TECHNOLOGICAL INSTITUTE
DFD
CPKelco A HUBER COMPANY
SAN Electro Heat
ELFORSK
Labotek

Electrification of processes and technologies for Danish Industry
Elforsk project 350-038

Appendix C
March 2021

By
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Abstract

The development of the Danish energy system tends towards significantly increasing production of electricity from renewable sources – in particular wind power. Hence, the energy system will be extensively electrified. 20 % of the energy is used in industrial processes, which may be an important focus area for electrification. The project has analyzed the potential realization of optimal substitution of process heating in industry based on combustion of fossil fuels with fully electricity-based heat.

The main purpose of the project was to analyze and identify substitution of process heat from fossil fuels as currently used in industry with electricity-based heat.

The project has analyzed how processes in specific industries are best converted to electricity-based heating, and as a consequence may increase efficiency and flexibility. Electrification can take place indirectly by conversion to fuels based on power-to-X, or directly by converting to electricity-based heating, by heat pumps or electric heating. This project focuses on the latter. Heat pumps are highly efficient, but are limited by e.g., temperature, while electric heating provides a potential for flexibility, in particular when using storage. The project includes detailed analyses of processes found in pectin production, milk powder production, brewing, plastics production and steam laundry. These cases may be seen as representative for a significant share of the manufacturing industry and involve options for process integration as well as high temperature processes.

Throughout the project, a procedure for investigating electrification potential has been developed. This involves mapping the individual energy-demanding processes, analyzing the potential for heat recovery by process integration, assessing the potential for using alternative technologies, defining electrification scenarios, calculating electrified process scenarios with a focus on energy, economics and CO_2 emission. The method has been continuously developed throughout the project but has been used on the basis of the same basic idea. The method has been used both for the overall analysis of

the industry and for the individual cases.

The presented analyzes show that electrification is possible and technically feasible for a significant part of the Danish industrial process heating needs. It has been found that the need for fuels can be reduced to 10 % of the current use, while the remaining use can be electrified. This in turn will reduce the need to about two-thirds of the current one.

For some of the case studies, e.g. milk powder and pectin production, full electrification can take place through energy integration, use of mechanical steam compression, heat pumping and electric heating. Current heat pump technology allows temperatures up to 100 °C, but the technology needs further development for higher temperatures. From this perspective, the available low temperature sources for the heat pumps are also important, as temperature lift significantly affects the performance of the heat pump.

The project has contributed with overall electrification plans for some of the cases, primarily pectin production. Part of this has involved assessment of technology from SAN Electro Heat for direct heating of processes that cannot use heat pumps and the need for further development of these.

For Labotek, a new solution has been developed during the project for drying plastic granulate with recovery of excess heat. This solution is implemented in Labotek's products and in operation in the industry. A further development of the solution with a heat pump has been analyzed and could provide further process improvement.

The project has thus found a significant potential for electrification in Danish industry. The project also includes an analysis of bottlenecks in the conversion to electrification, which should be included in the picture. These are grouped as being economic, technical, organizational or risk-related. They include technical limitations in current heat pump technology and costs of conversion, but also requirements for security of supply and the company's willingness to convert to a large extent and to use less well-known technology.

For industrial production, the potential for sector coupling by using electricity flexibly is less clear. The industry will most often need to utilize the capacity for process heating fully with a high number of operating hours per year, but for batch processes and by investing in extra capacity, it is possible to utilize the potential for energy storage provided that it does not affect the final product, e.g. due to temperature changes.

From an economic perspective the electrification is feasible for a number of the analyzed cases. However, full electrification will require further development of technology and frame conditions related to investment and operating cost as well as possible subsidies and taxation related to greenhouse gas emission. In this respect, it is important to keep in mind that electricity production in Denmark presently causes greenhouse gas emissions, and that sustainable electrification requires significant development of the electricity system.

Resumé

Udviklingen af det danske energisystem går mod en markant stigende produktion af elektricitet fra vedvarende kilder - især vindkraft. Derfor vil energisystemet i høj grad blive elektrificeret. 20 % af energien bruges i industrielle processer, som dermed er et vigtigt fokusområde for elektrificering. Projektet har analyseret den potentielle realisering af optimal erstatning af procesopvarmning i industrien baseret på forbrænding af fossile brændstoffer med fuldt elbaseret varme.

Hovedformålet med projektet har været at analysere og identificere erstatning af procesvarme fra fossile brændstoffer, som det i øjeblikket anvendes i industrien, med elbaseret varme.

Projektet har analyseret, hvordan processer i specifikke industrier bedst konverteres til elbaseret opvarmning, og som en konsekvens kan øge effektiviteten og fleksibiliteten. Elektrificering kan ske indirekte ved omdannelse til brændstoffer baseret på power-to-X eller direkte ved konvertering til elbaseret opvarmning ved hjælp af varmepumper eller elektrisk opvarmning. Dette projekt fokuserer på sidstnævnte. Varmepumper har høj effektivitet, men er begrænset af fx temperatur, mens elektrisk opvarmning giver et potentiale for fleksibilitet, især når det kobles med energilagring. Projektet inkluderer detaljerede analyser af processer i pektinproduktion, mælkepulverproduktion, bryggerier, plastproduktion og dampvaskerier. Disse cases kan ses som repræsentative for en betydelig andel af fremstillingsindustrien og involverer muligheder for procesintegration samt højtemperaturprocesser.

Igennem projektet er udviklet en procedure for undersøgelse af elektrificeringspotentiale. Dette indebærer kortlægning af de enkelte energikrævende processer, analyse af potentiale for varmegenvinding ved procesintegration, vurdering af potentiale for anvendelse af alternative teknologier, definition af elektrificeringsscenarier, beregning af elektrificerede processcenarier med fokus på energi, økonomi og CO_2-udlending. Metoden er løbende blevet udviklet gennem projektet men er benyttet ud fra den samme grun-

didé. Metoden har været anvendt både for den samlede analyse af industrien og for de enkelte cases.

De præsenterede analyser viser, at elektrificering er mulig og teknisk gennemførlig for en væsentlig del af det danske industrielle procesopvarmningsbehov. Det er fundet, at behovet for brændsler kan reduceres til 10 % af den nuværende anvendelse, mens den resterende anvendelse kan elektrificeres. Dette vil igen reducere behovet til omkring to tredjedele af det nuværende.

For nogle af casestudierne, fx mælkepulver- og pektinproduktion, kan fuld elektrificering finde sted ved energiintegration, anvendelse af mekanisk dampkomprimering, varmepumpning og elektrisk opvarmning. Den nuværende varmepumpeteknologi tillader temperaturer på op til 100 °C, men teknologien har brug for yderligere udvikling for højere temperaturer. Set fra dette perspektiv er de til rådighed værende lavtemperaturkilder for varmepumperne også vigtige, da temperaturløft påvirker varmepumpens effektivitet betydeligt.

Projektet har bidraget med samlede elektrificeringsplaner for flere cases, primært pektinproduktion. En del af dette har involveret vurdering af teknologi fra SAN Electro Heat til direkte opvarmning af processer som ikke kan anvende varmepumper og behov for videre udvikling af disse.

For Labotek er der undervejs i projektet udviklet en ny løsning for tørring af plastgranulat med genvinding af overskudsvarme. Denne løsning er implementeret i Laboteks produkter og i drift i industrien. En videreudvikling af løsningen med en varmepumpe er analyseret og vil kunne give yderligere procesforbedring.

I projektet er der dermed fundet store potentialer for elektrificering i dansk industri. Projektet indeholder også en analyse af flaskehalse i omstilling til elektrificering, hvilket naturligvis skal med i billedet. Disse er grupperet som værende økonomiske, tekniske, organisatoriske eller risiko-relaterede. Herunder kan nævnes tekniske begrænsninger i nuværende varmepumpeteknologi og økonomiske omkostninger ved omstilling, men også krav til forsyningssikkerhed og virksomhedens villighed til at omstille i stor udstrækning og til at anvende mindre velkendt teknologi.

For den industrielle produktion er potentialet for sektorkobling ved at anvende el fleksibelt mindre åbenlyst. Industrien vil oftest have behov for at udnytte kapaciteten til procesopvarmning fuldt ud med et højt antal driftstimer årligt, men for batchprocesser og ved investering i ekstra kapacitet er der mulighed for at kunne udnytte potentialet for lagring af energi under forudsætning af at det ikke giver indflydelse på det færdige produkt, fx grundet temperaturændringer.

Ud fra et økonomisk perspektiv er elektrificering mulig for en række af de analyserede tilfælde. Fuld elektrificering vil dog kræve yderligere udvikling af teknologi og rammebetingelser relateret til investerings- og driftsomkostninger samt muligvis støtte og beskatning i forbindelse med CO_2-udledning. I den henseende er det vigtigt have in mente, at den nuværende elproduktion i Danmark forårsager CO_2-udledning, og at bæredygtig elektrificering kræver en betydelig udvikling af elsystemet.

C Industrial case studies

ELFORSK Projekt: ELIDI

Electrification of a Milk Powder Factory and an Industrial Laundry

Fabian Bühler, Fridolin Müller Holm, Benjamin Zühlsdorf and Brian Elmegaard

Department of Mechanical Engineering, Technical University of Denmark
Viegand Maagøe A/S
Teknologisk Institut

Agenda

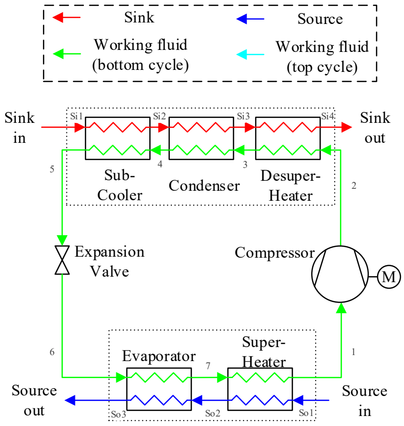
- Introduction
- Method
  - Approach
  - Heat pump
  - Economics
- Case studies
  - Milk Powder Production
  - Industrial Laundry

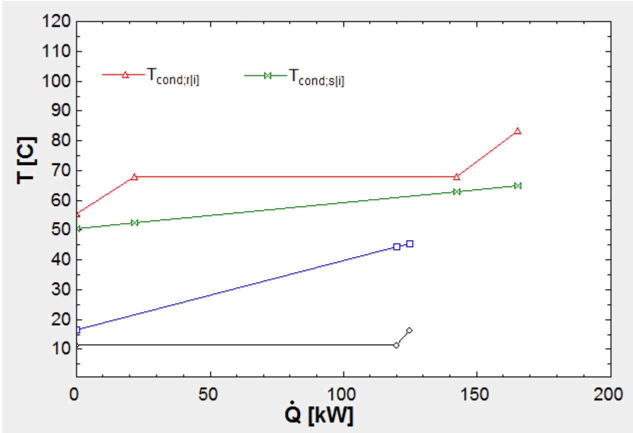
(for each case study:)
- Case Description
- Electrification Scenarios
- Energy analysis
- Economic analysis

Method
Overall Approach

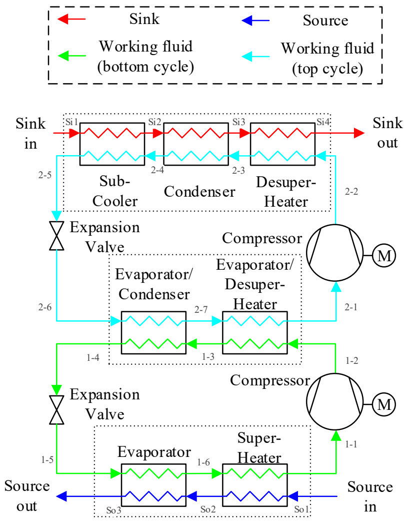
- Data collection and energy mapping
- Thermodynamic models of existing system
- Energy (and exergy) analysis
- Energy optimization (waste heat recovery and process integration)
- Electrification
  - Heat Pump integration
  - Central electrification
- Economic analysis
- Sensitivity analysis

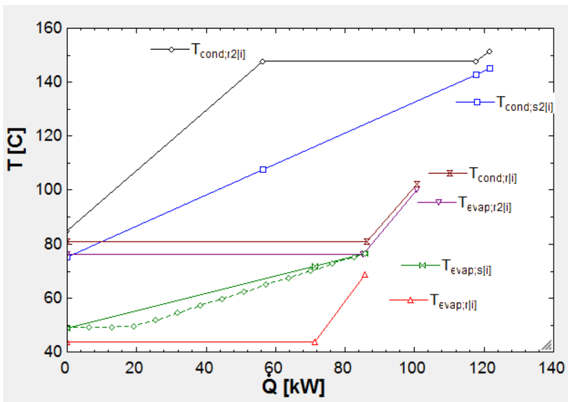
Continuous Tunnel Washer
Single Stage Heat Pump



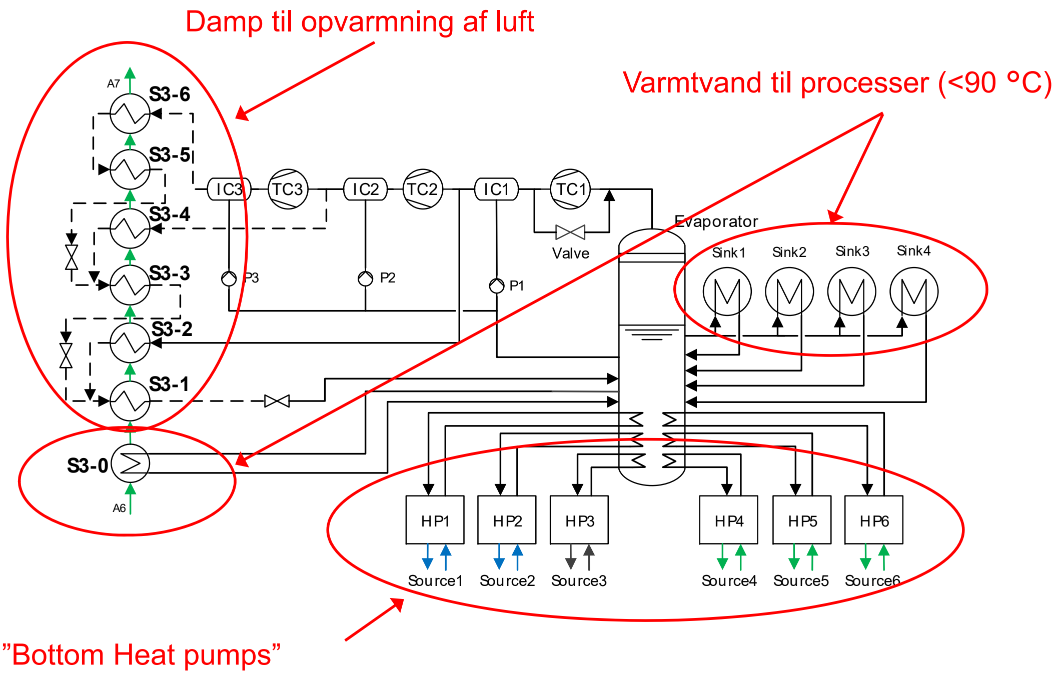


Method
Two Stage Heat Pump



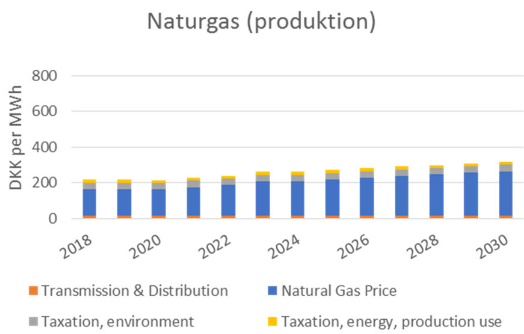


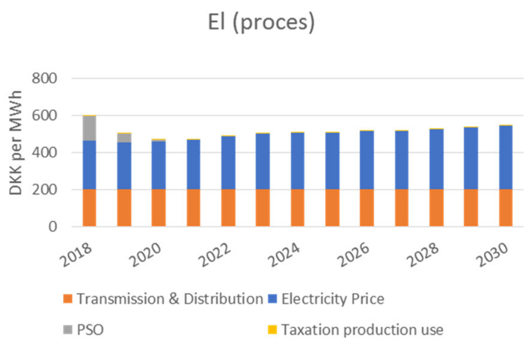
Method
Central Varmepumpe



Economic analysis electrification laundry
Investment Assumptions

- Lifetime of investment 20 years
- Total module costs incl. auxiliary facilities and grasroot factor
- Inflation 2 % p.a.
- Discount rate 5 % p.a.
- Boiler efficiency 94 %
- Steam transmission and distribution efficiency 90 %





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Case Study
Milk Powder Production

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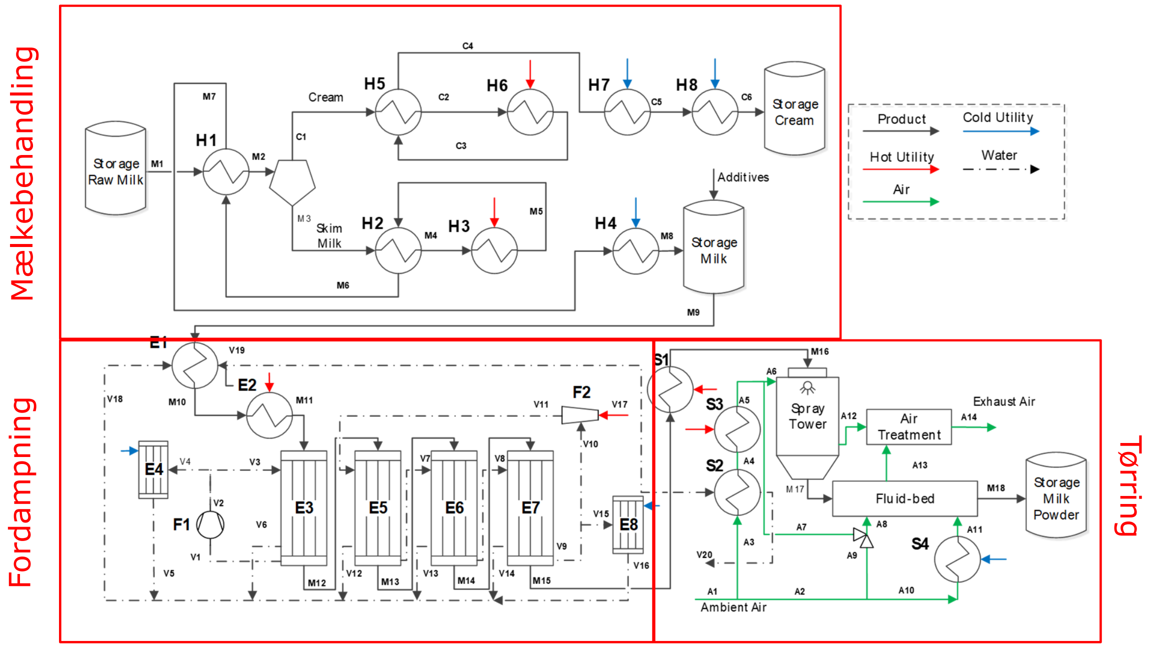
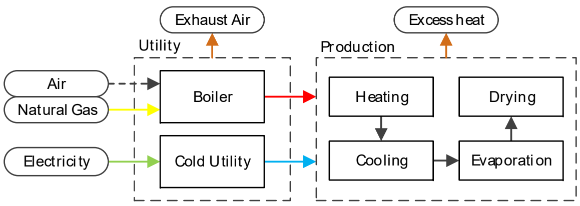
Milk powder case study
Process flow diagram

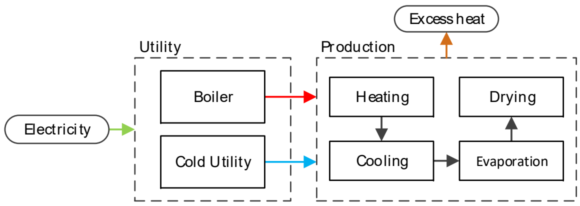


Milk powder case study
Strategier til elektrificere

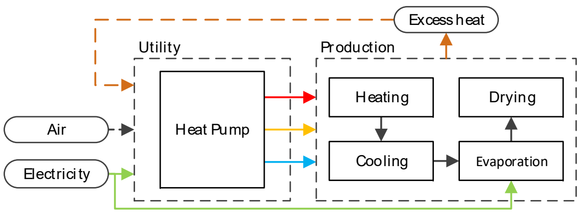
BAU



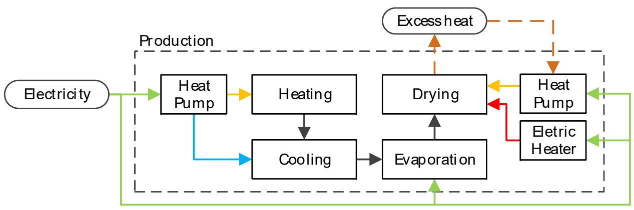
BAU – Elektrisk + energioptimering



Central Varmepumpe



Decentral Varmepumper

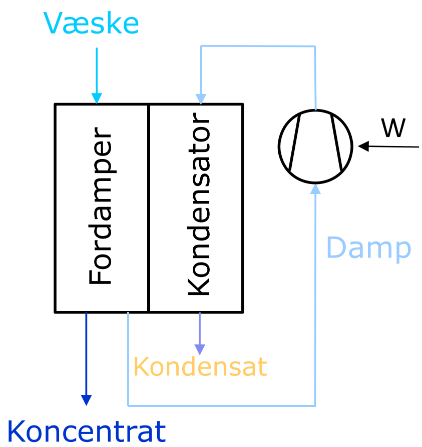


Milk powder case study
Muligheder

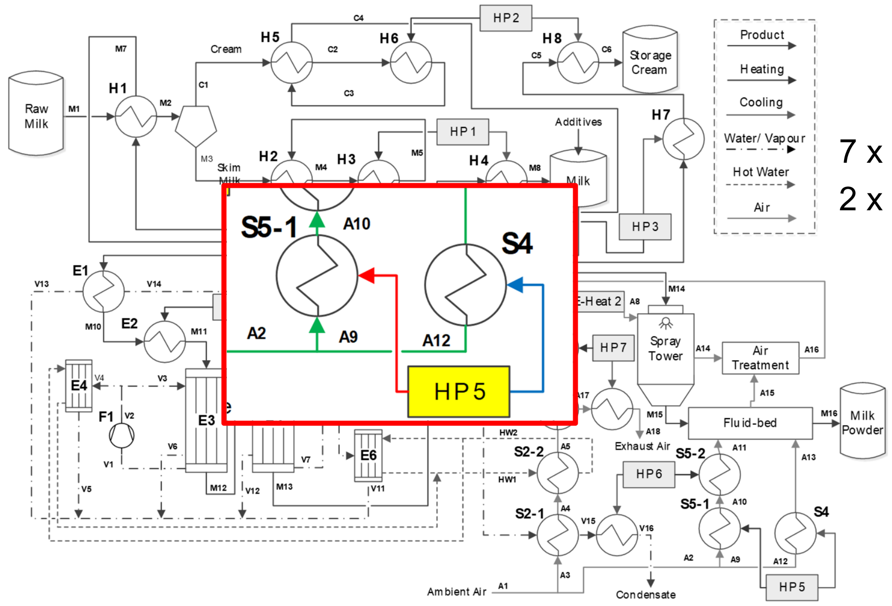
Energieffektivisering
- Varmegenvinding på kondenser
- Luftforvarmning med tørringsluft

Elektrificering ved procesændringer
- Fordamper med MVR, i stedet for TVR
  - TVR 3 stages: 0.140 kWh/kg_{vand}
  - MVR 1 stage: 0.015 kWh/kg_{vand}

Kilder til varmepumper
- Udnyttelse af varme fra tørringsluft
- Udnyttelse af varme fra køling
- Udendørsluft

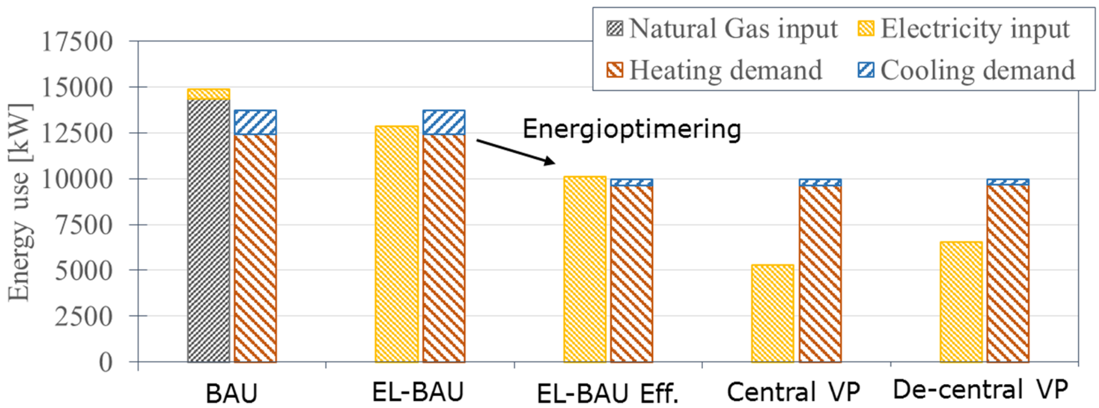


Milk powder case study
Decentral Varmepumper + Elpatron



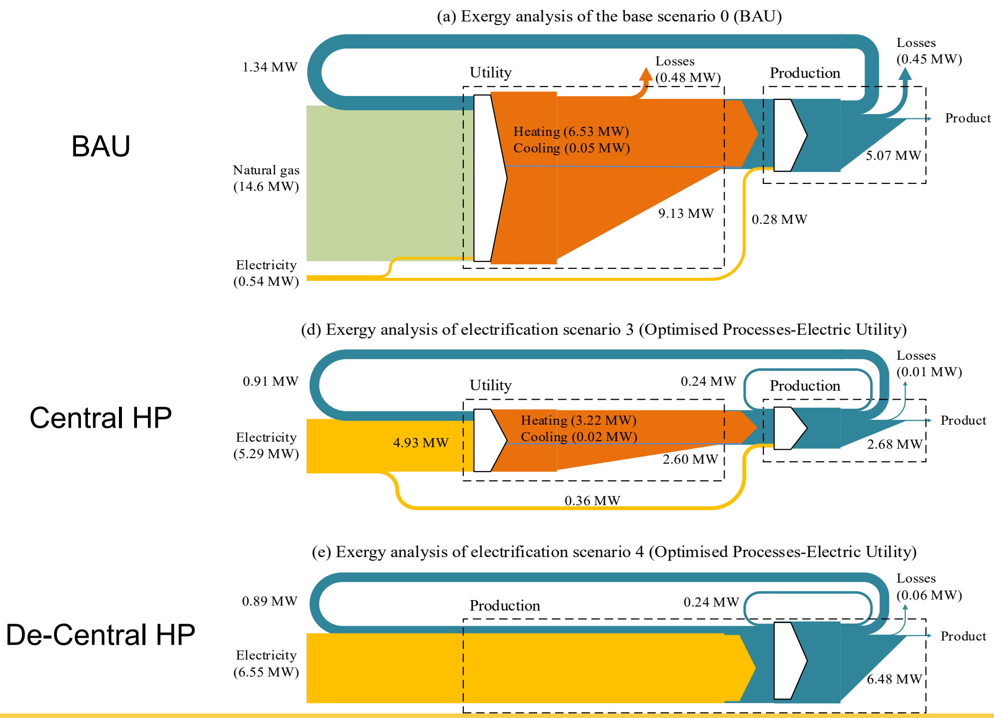
7 x Varmepumper
2 x El-Heater

Milk powder case study
Resultater – Energi I

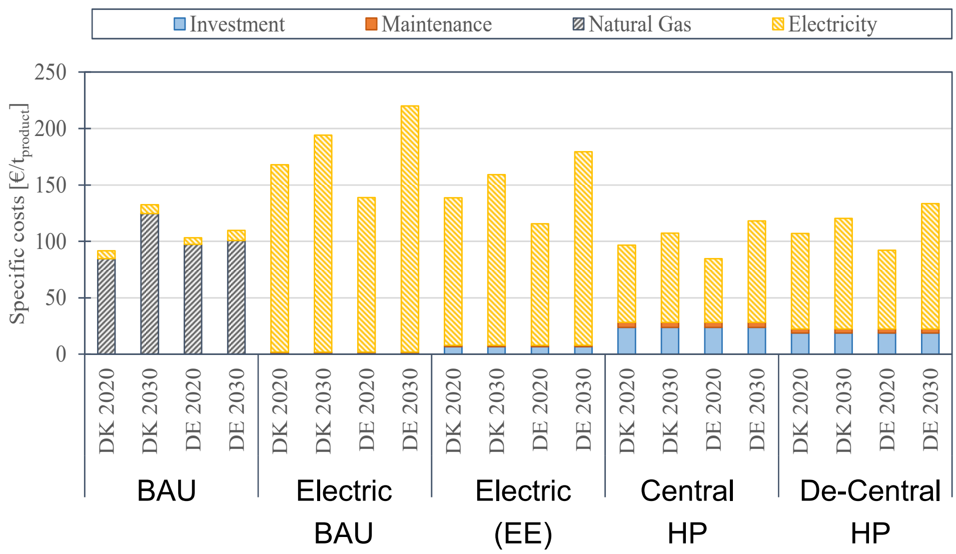


- Central varmepumpe: COP på 1.95
- Decentral varmepumpe: COP på 1.57
  COP mellem 1 og 5.2
- Kølebehov dækket med varmepumper

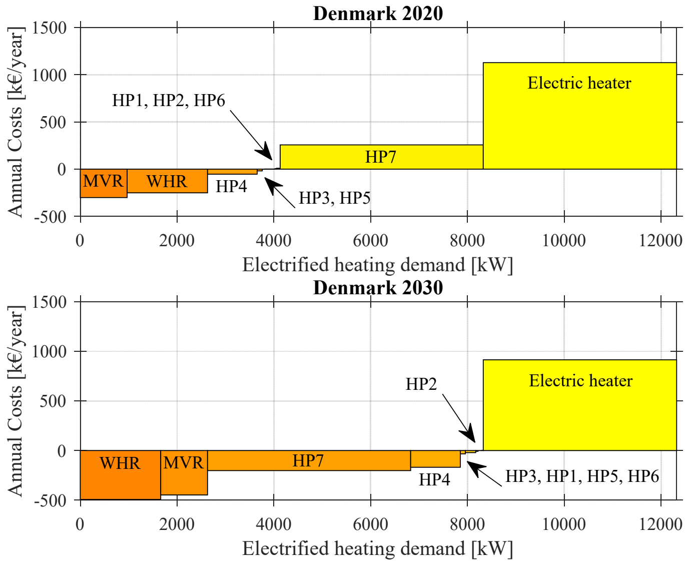
Milk powder case study
Resultater Exergi



Milk powder case study
Resultater Økonomi



Milk powder case study
Resultater Økonomi



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.

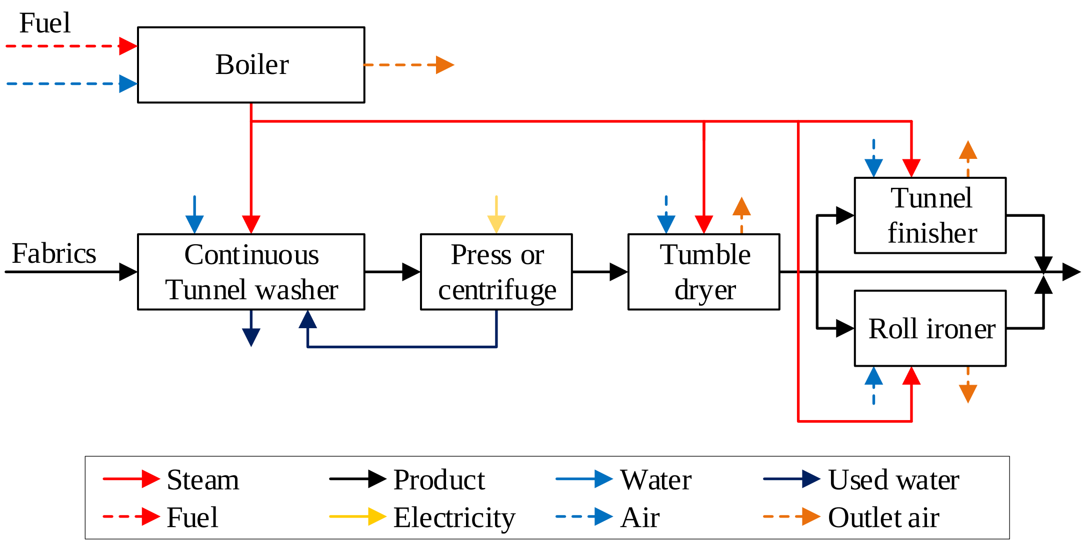


Fig. 1: Process description of the industrial laundry.

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.

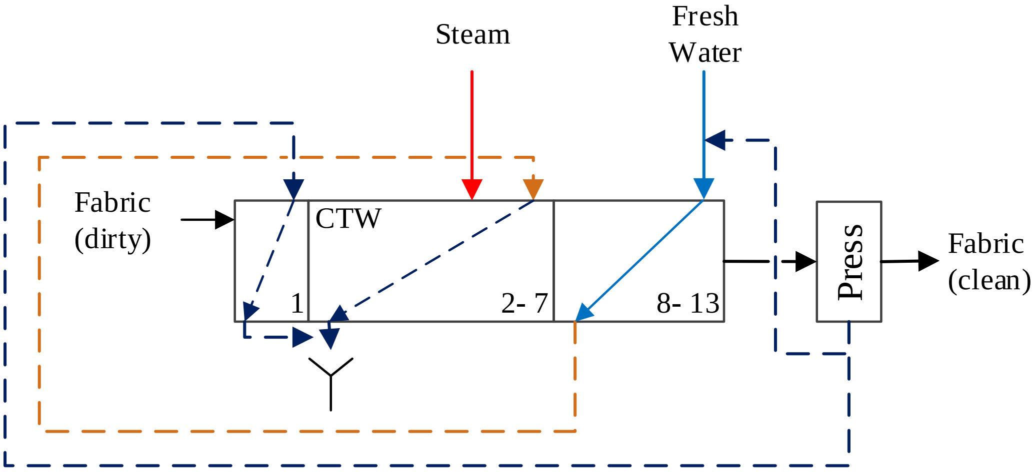


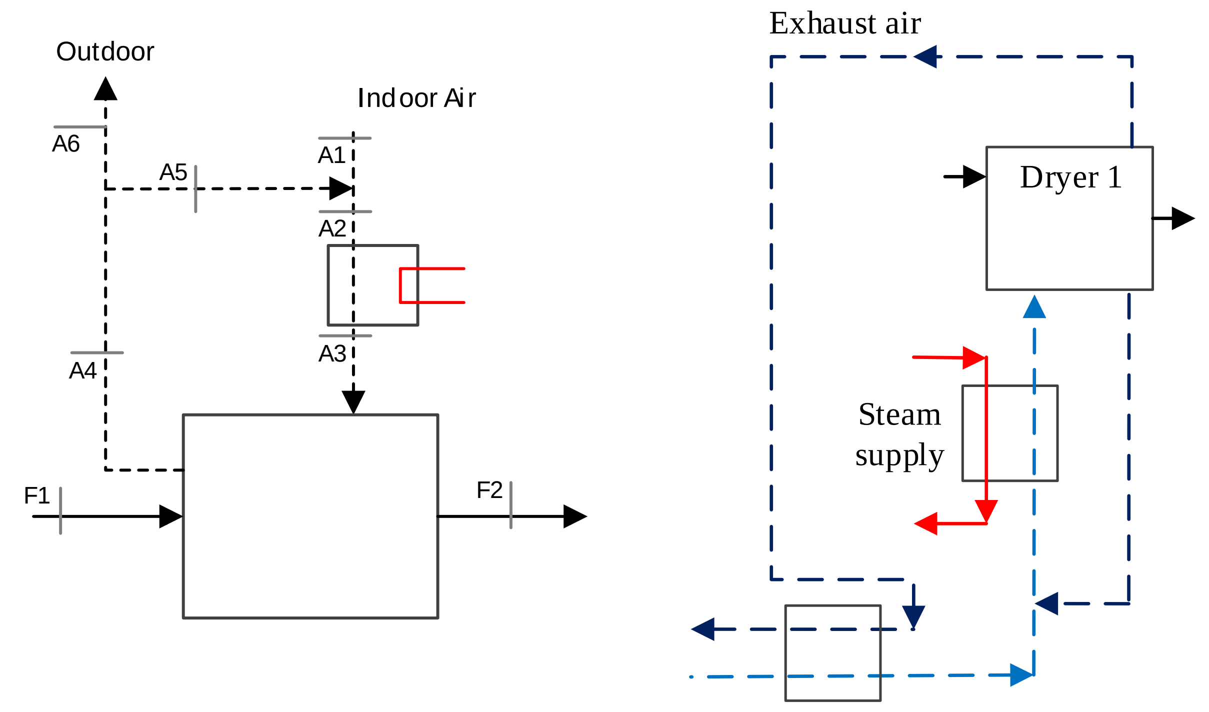
Fig. 2: Process description of the continuous tunnel washer (CTW).

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)

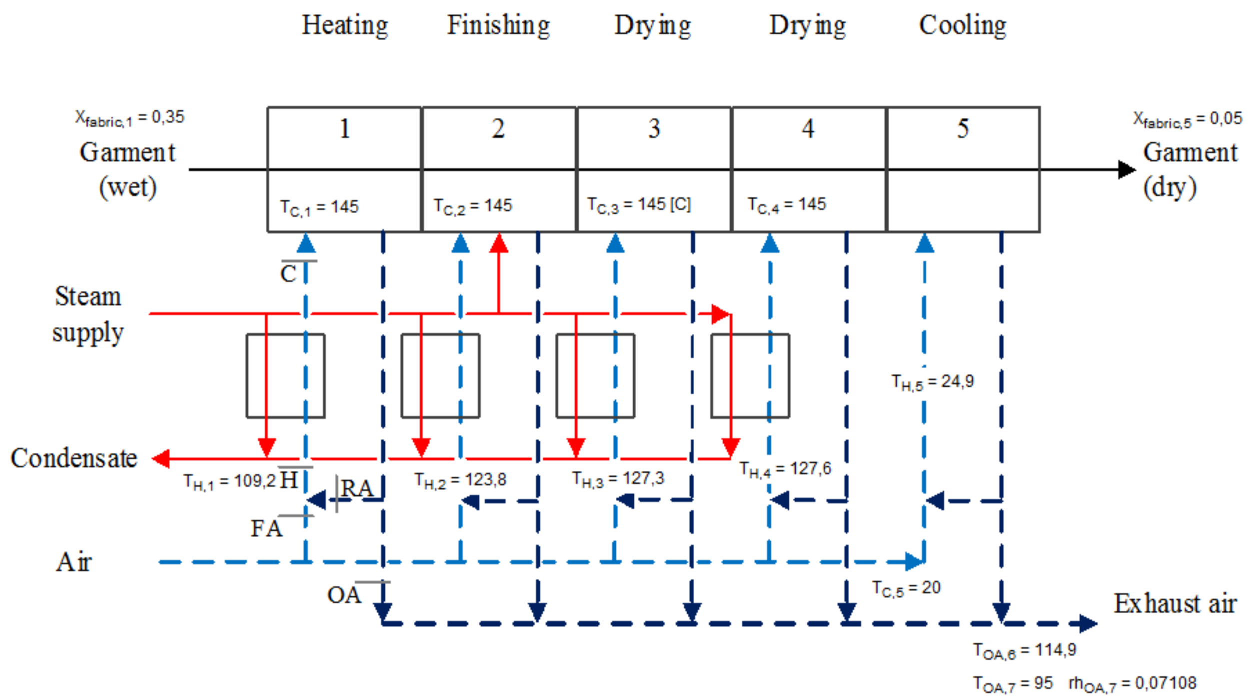


Fig. 4. Schematic of the tunnel finisher with the main temperature set-points (T) in °C, water content of the fabric (X) in kg/kg and relative humidity of the air (rh).

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).

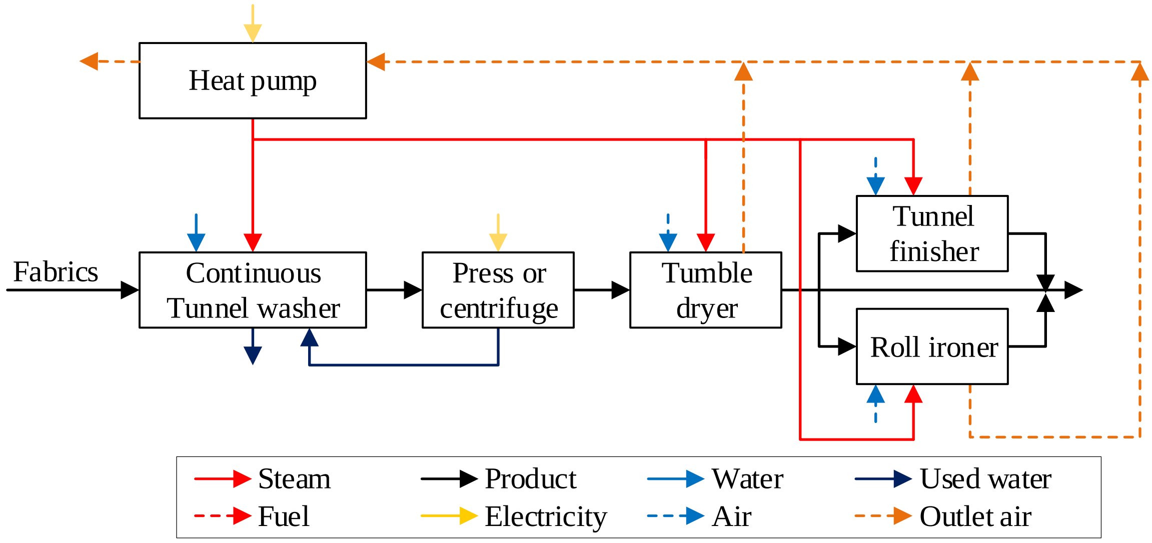


Fig. 5. Central electrification strategy of the laundry based on central steam generating heat pump.

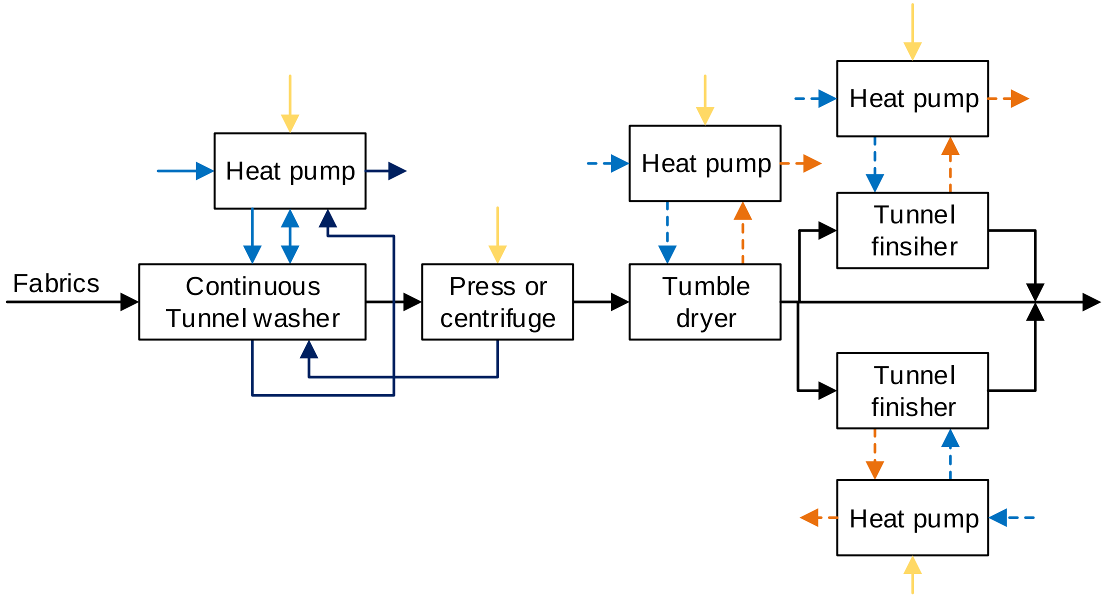


Fig. 6. Decentral electrification strategy of the laundry.

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.

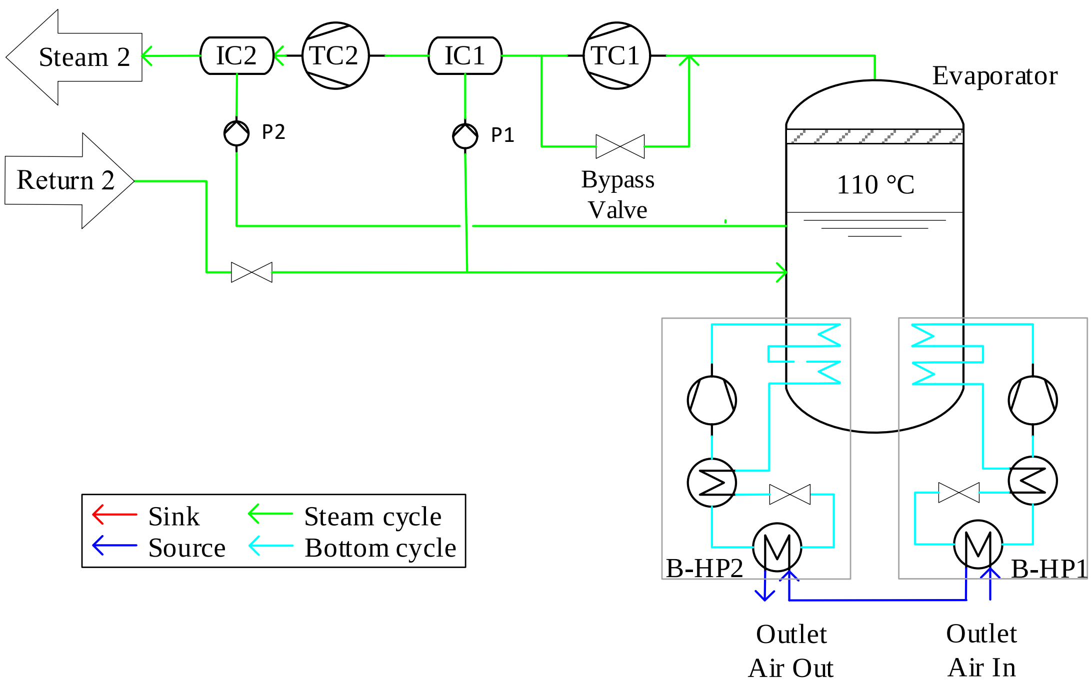


Fig. 7. Steam generation heat pump in multistage cascade system.

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.

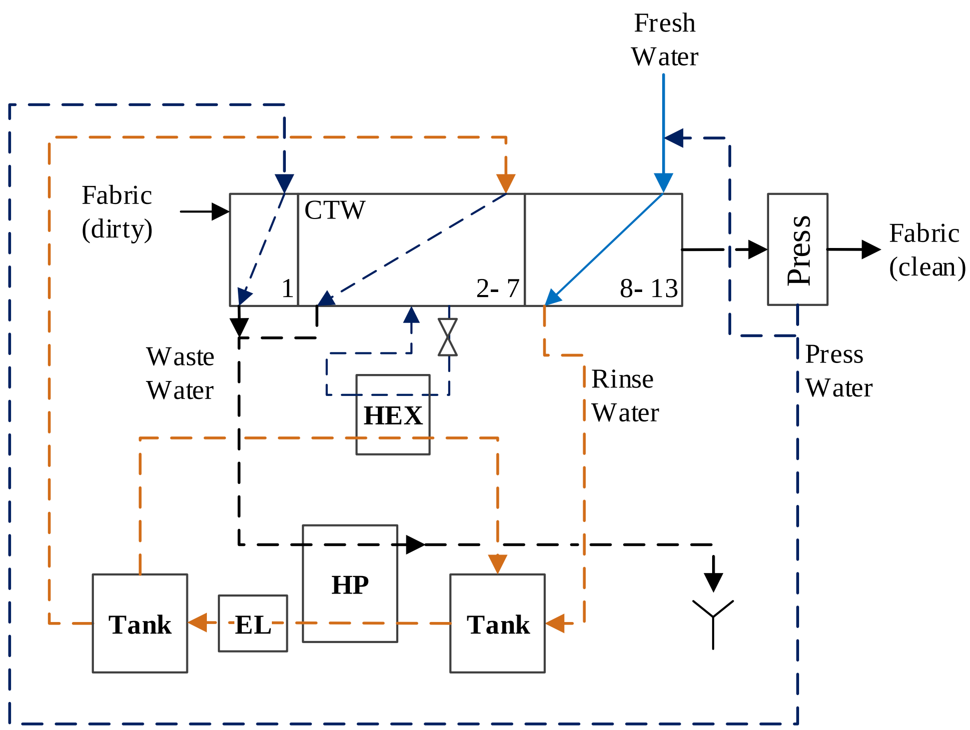


Fig. 8: Electrification of the CTW with waste heat recovery.

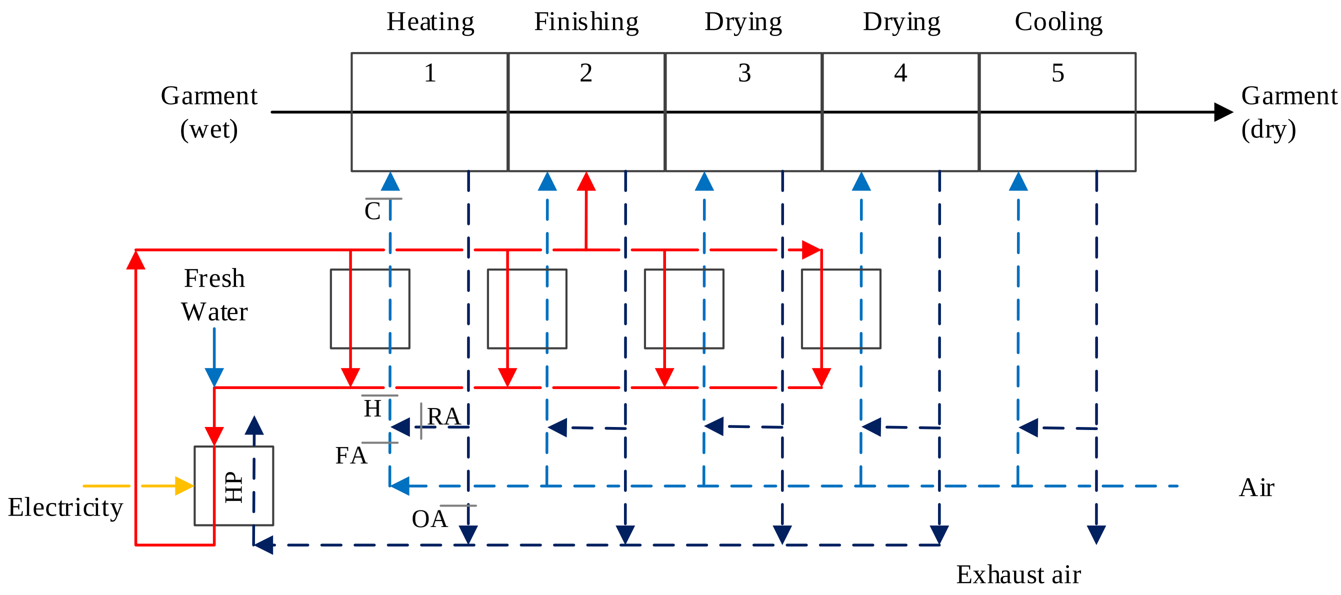


Fig. 9: Electrification of the tunnel finisher with waste heat recovery.

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.

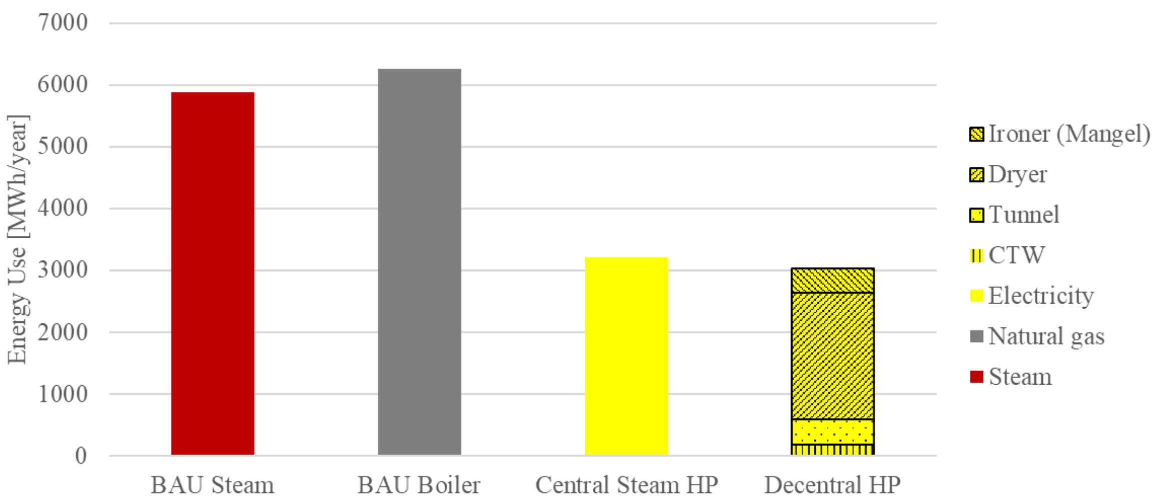


Fig. 10: Summary of the energy use before electrification (BAU) and after electrification for the central and decentral solution.

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.

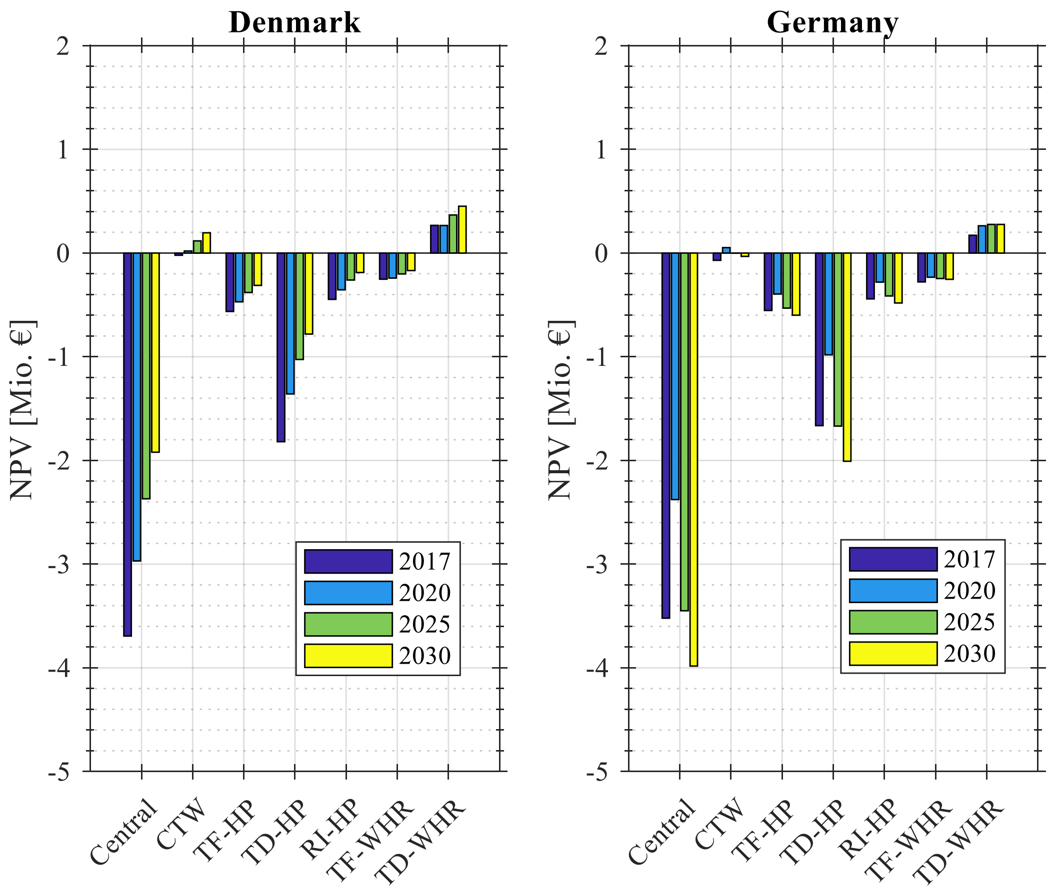


Fig. 11: Net Present Value for investments in central electrification (Central), the decentral electrification (CTW-Continuous Tunnel Waster, TF- Tunnel Finisher, TD – Tumble Dryer and RI – Roll Ironer) and alternative waste heat recovery (WHR) for the TF and TD without electrification.

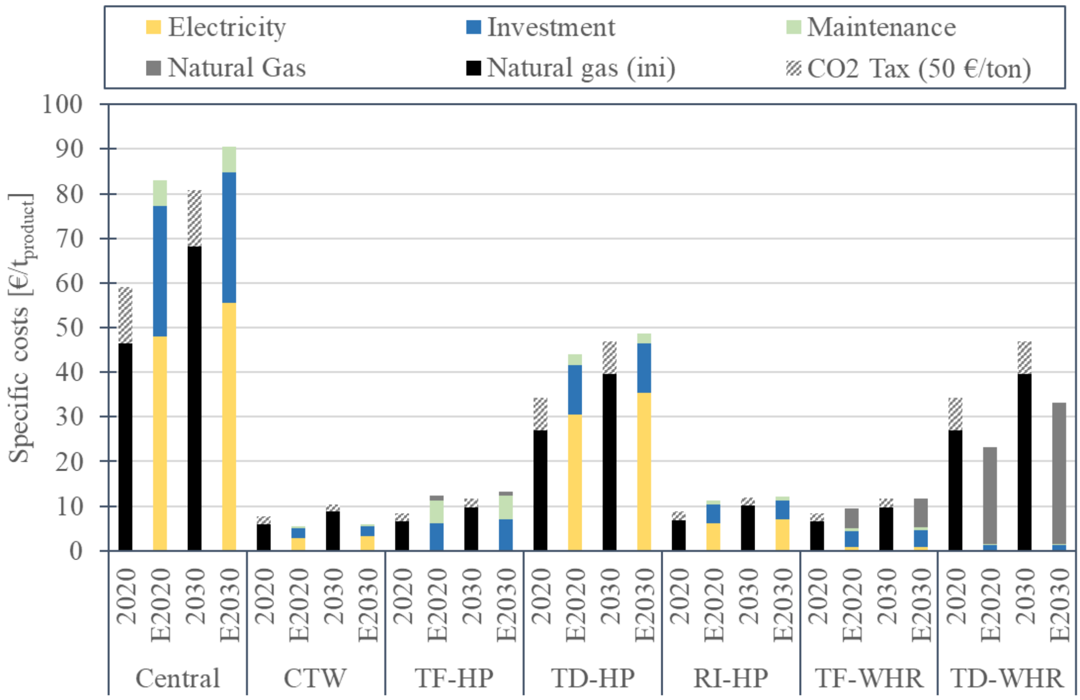


Fig. 12: Specific energy related costs in the years 2020 and 2030 without and with electrification (E) for the different investment opportunities.

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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ELFORSK Projekt: ELIDI

Electrification of a Milk Powder Factory and an Industrial Laundry

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Viegand Maagøe A/S

Teknologisk Institut

Agenda

- Introduction
- Method
  - Approach
  - Heat pump
  - Economics
- Case studies
  - Milk Powder Production
  - Industrial Laundry

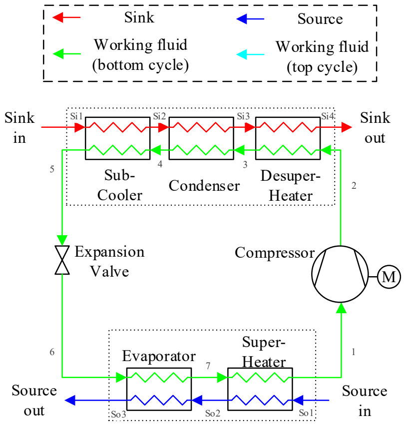
(for each case study:)

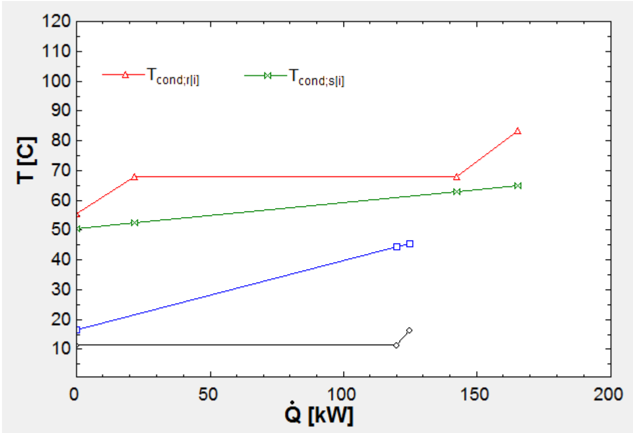
- Case Description
- Electrification Scenarios
- Energy analysis
- Economic analysis

Method
Overall Approach

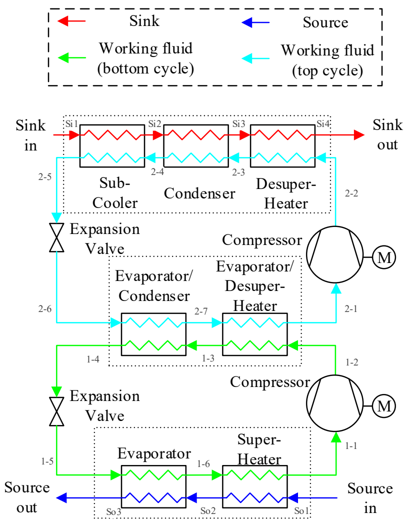
- Data collection and energy mapping
- Thermodynamic models of existing system
- Energy (and exergy) analysis
- Energy optimization (waste heat recovery and process integration)
- Electrification
  - Heat Pump integration
  - Central electrification
- Economic analysis
- Sensitivity analysis

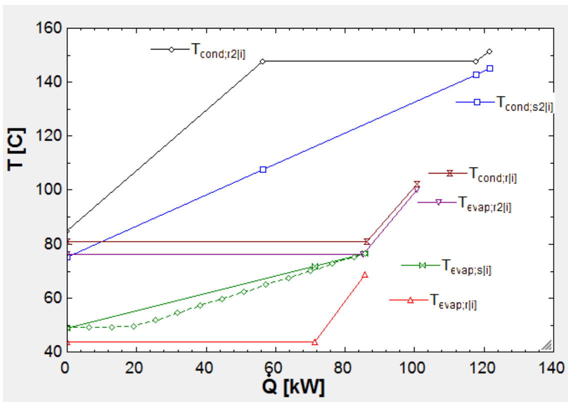
Continuous Tunnel Washer
Single Stage Heat Pump



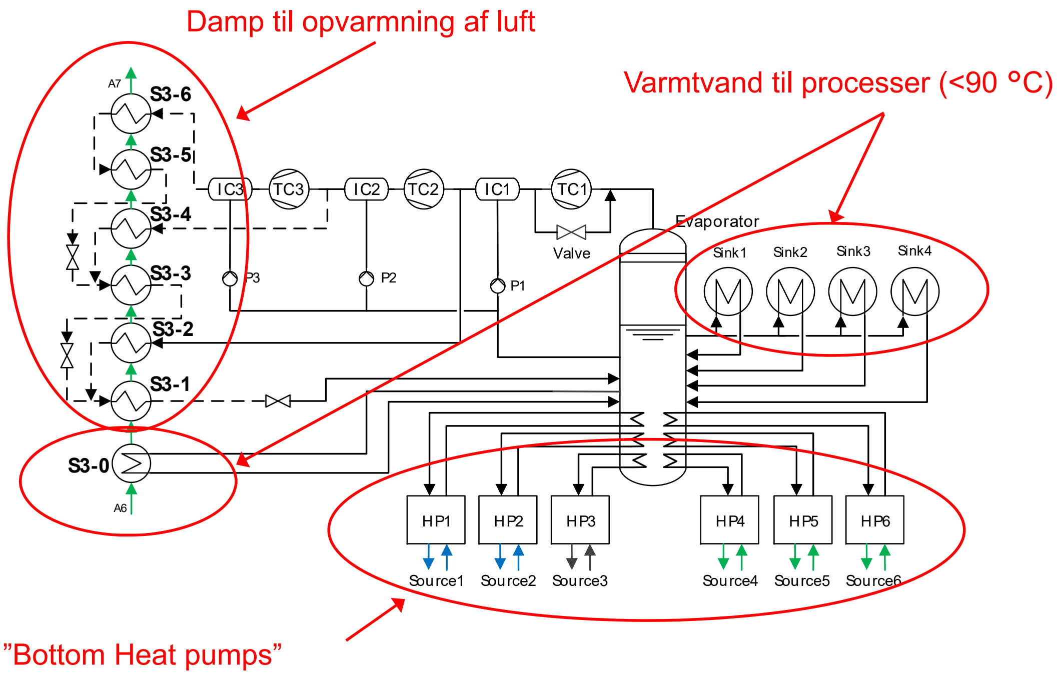


Method
Two Stage Heat Pump



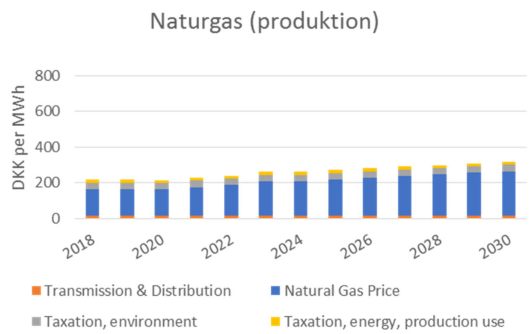


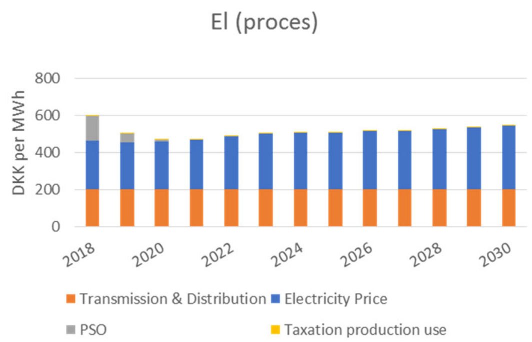
Method
Central Varmepumpe



Economic analysis electrification laundry
Investment Assumptions

- Lifetime of investment 20 years
- Total module costs incl. auxiliary facilities and grasroot factor
- Inflation 2 % p.a.
- Discount rate 5 % p.a.
- Boiler efficiency 94 %
- Steam transmission and distribution efficiency 90 %

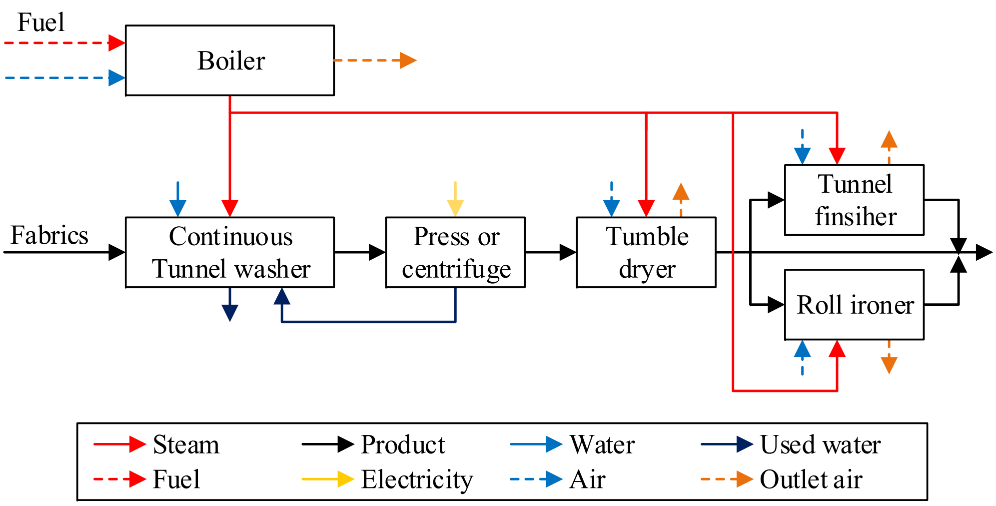




Laundry Case Study

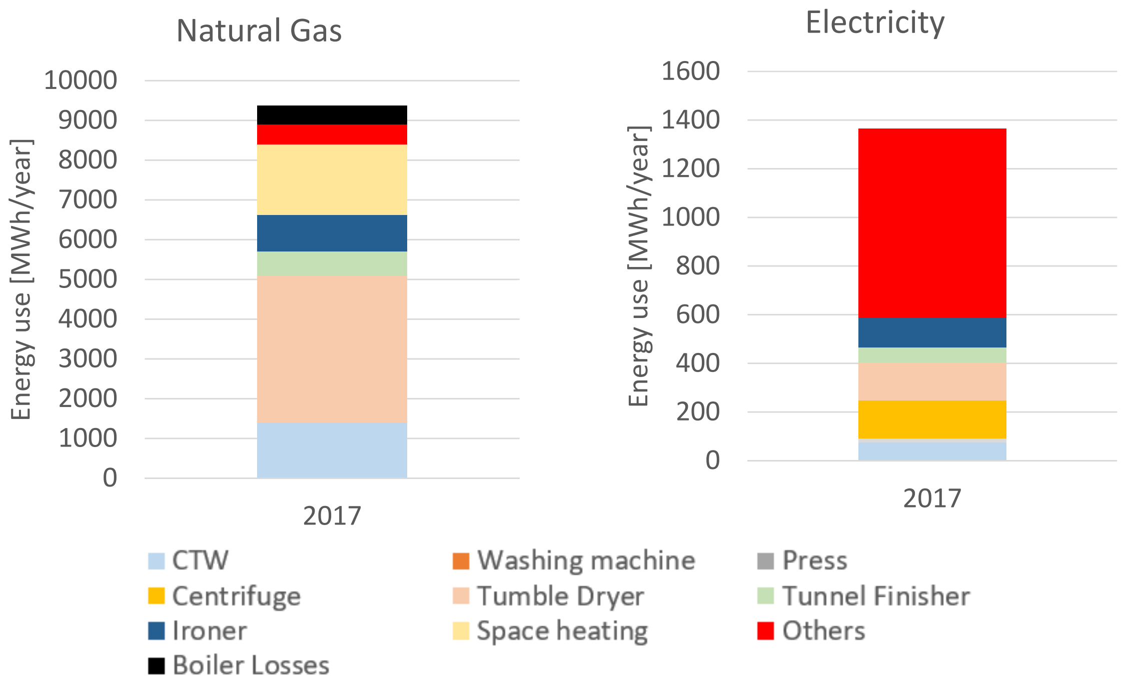
De Forenede Dampvaskerier (DFD)

Overall system diagram

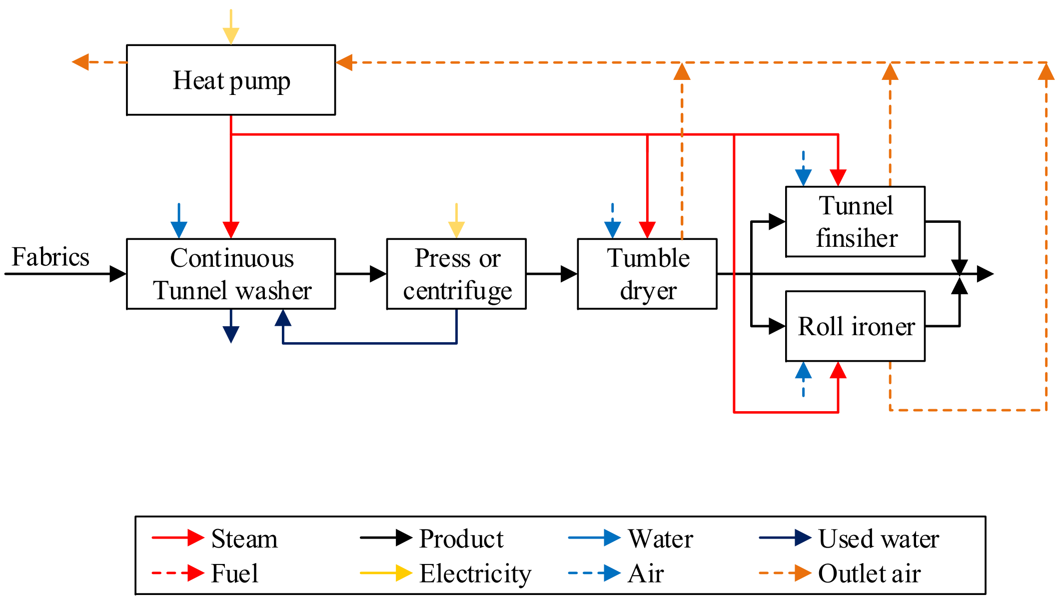


- Central utility boiler (8.2 MW @ 180°C/ 9 bar)

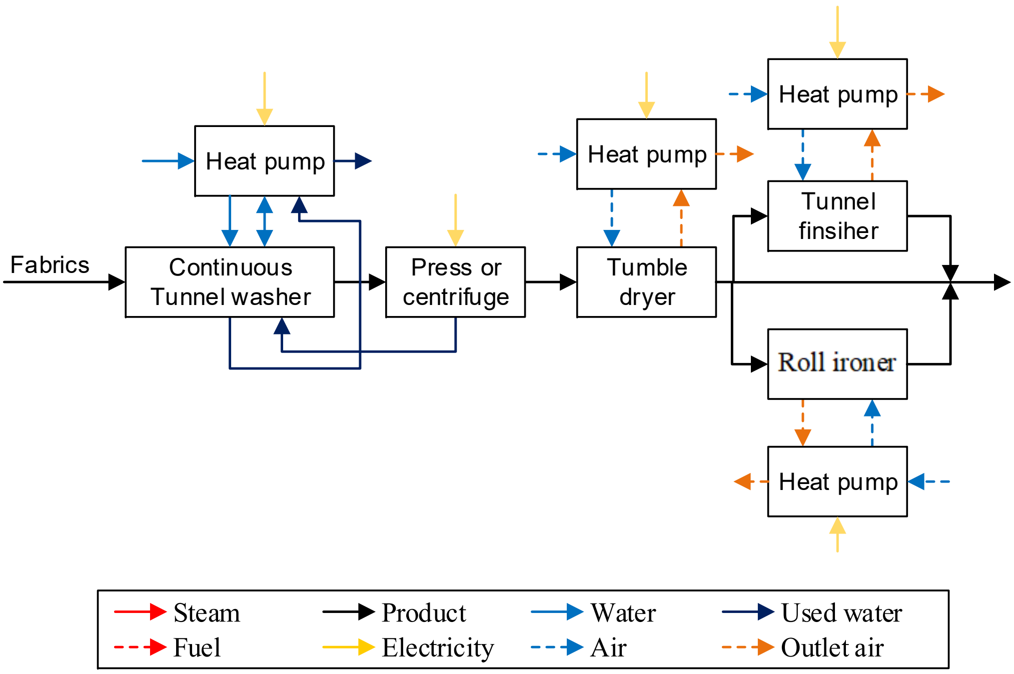
Laundry case study
Energy balance



Elektrificeringsstrategier Vaskeri
Central Elektrificering



Elektrificeringsstrategier Vaskeri
De-central Elektrificering



Overblik modellering og elektrificering

<table>
<tr><th></th><th>CTW</th><th>Tunnel finisher</th><th>Tumble dryers</th><th>Roll ironers</th></tr>
<tr><td>1. Beskrivelse</td><td colspan="4">System og komponenter</td></tr>
<tr><td>2. Modellering</td><td colspan="3">Termodynamisk model</td><td>-</td></tr>
<tr><td rowspan="3">3. Elektrificering</td><td rowspan="2">WHR + HP</td><td>WHR + HP</td><td>WHR</td><td>-</td></tr>
<tr><td colspan="3">Steam - HP</td></tr>
<tr><td colspan="4">Central heat pump</td></tr>
<tr><td>4. Økonomi</td><td colspan="4">NPV, SPT, Unit costs of heat</td></tr>
<tr><td>5. Sensitivitet</td><td colspan="4">Økonomi</td></tr>
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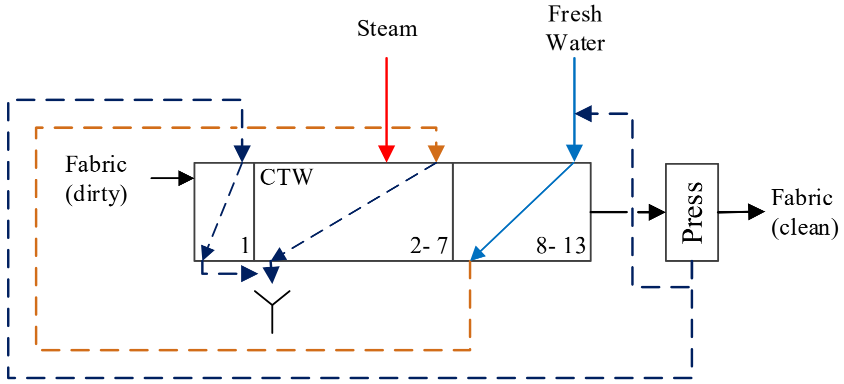
Continuous Tunnel Washer
Simplified View

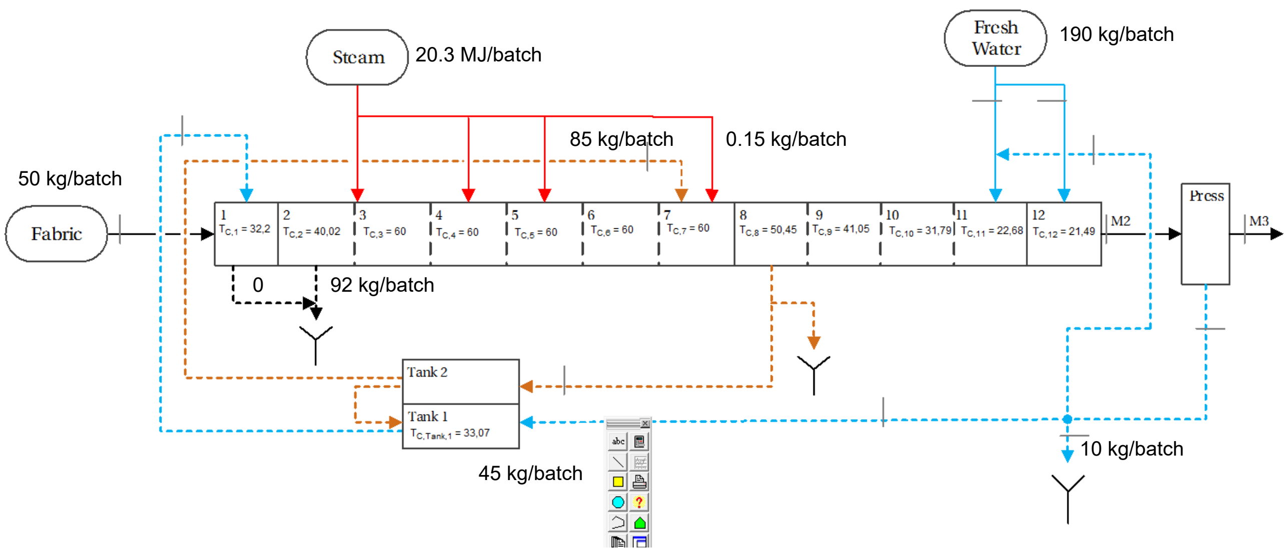


Continuous Tunnel Washer
Model

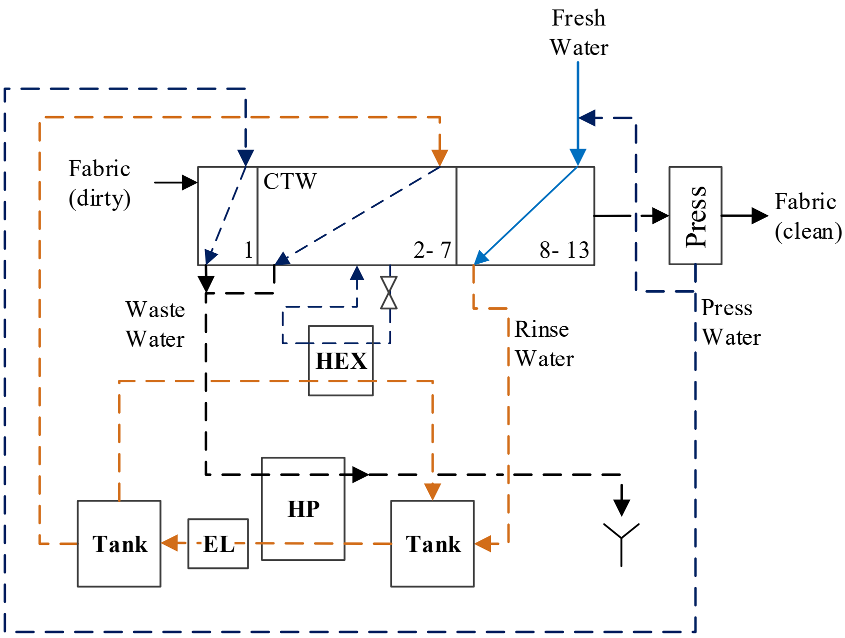
- Cycle time 150 s
- Batch size 50 kg
- No heat losses

- Complete mass transfer between chambers
- Target Temp. 60 C

- Optimized CTW
- Countercurrent operation



Continuous Tunnel Washer
Electrification and Waste heat recovery - Concept



Continuous Tunnel Washer
HP – Modelling & Results

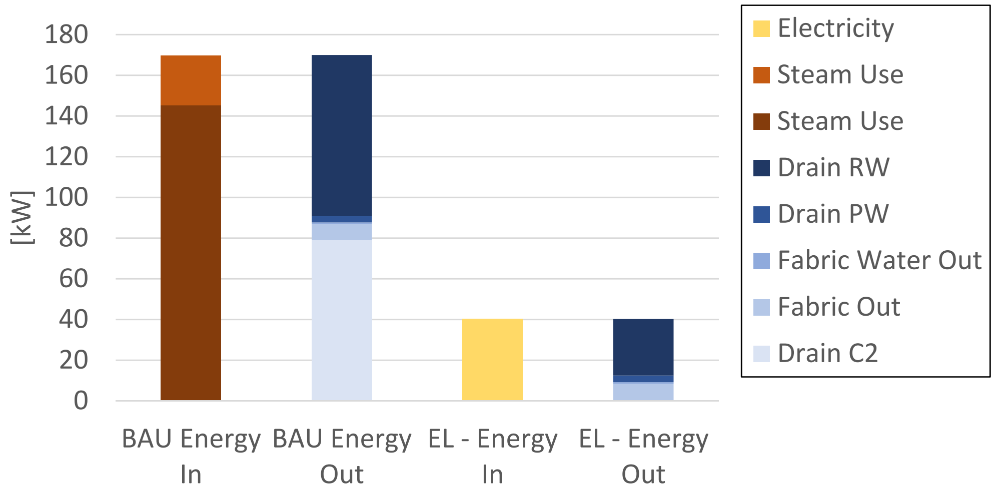
- COP theoretical: COP_L = 11.6
- COP model (simple cycle): COP = 4.1

} HP efficiency 35.3 %

- HP Electricity use: 3.36 kWh/100 kg_{fabric}
- Initial energy use: 9.31 kg_{steam}/batch (18.63 kg_{steam}/100 kg_{fabric})
  6.54 kWh/ batch (13.08 kWh/100 kg_{fabric})

DTU

Tunnel washer
Results – Energy analysis



		2015	2016	2017
BAU-Steam- Model	MWh/year	652	683	759
WHR-HP Electricity	MWh/year	155	162	180

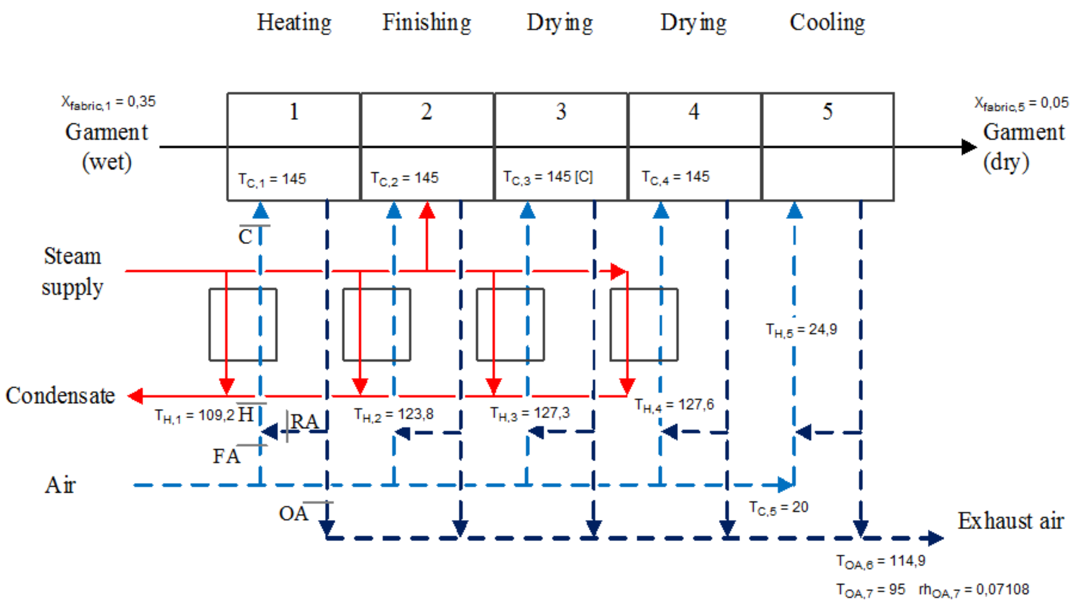
DTU

Tunnel finisher
Working principle

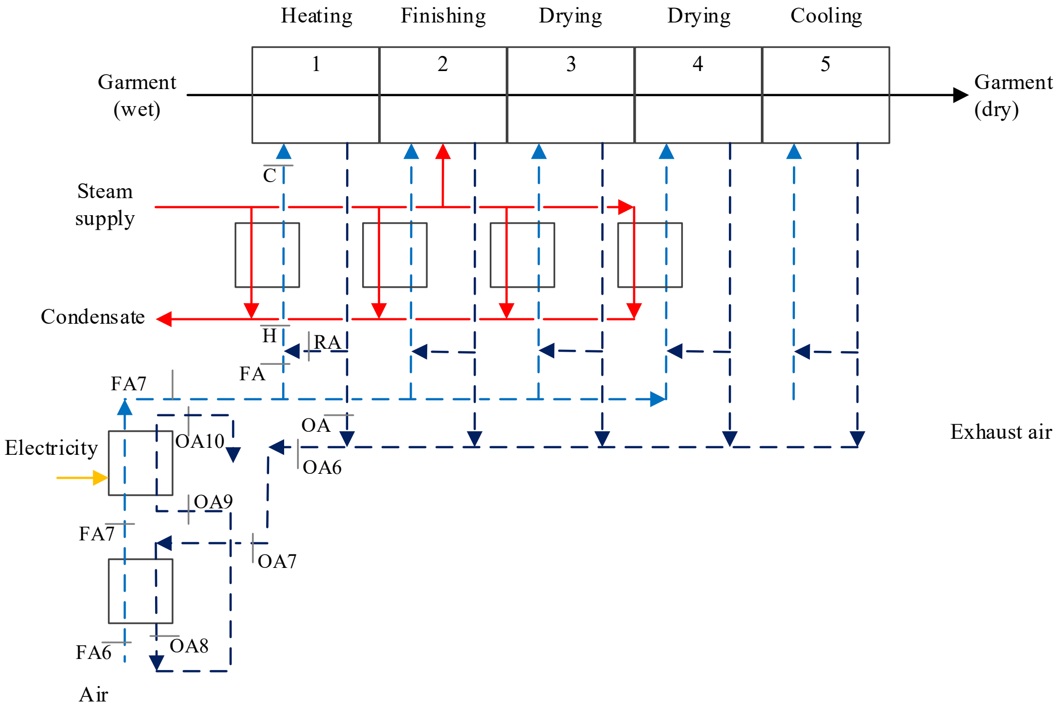
Working Principle
- Gas or steam heated
- Compartments
  - Heating with air at 145°C
  - Finishing with steam injection and hot air
  - Drying with air at 145°C
  - Cool down with ambient air

Assumptions
- Air recirculation fixed at 90 %
- Fixed air set-point temperature
- No heat losses
- No suction of ambient air

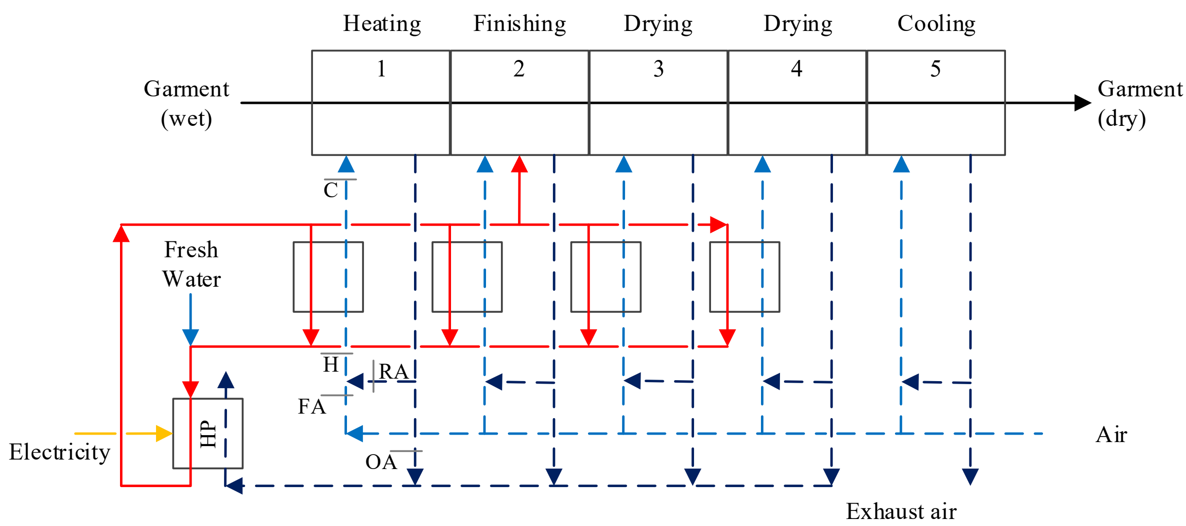
Tunnel finisher
Model



Tunnel finisher
Electrification Option 1



Tunnel finisher
Electrification Option 2



Tunnel finisher
Results

Electrification Option 1

- COP theoretical: $COP_L = 8.22$
- COP model (two stage): $COP = 3.4$

} HP efficiency 41.4 %

- System COP: $COP_S = 6.1$
- HP Electricity use: 35.74 kW (3.9 kWh/100 kg_{fabric})
- Steam use: 400.7 kW (43.3 kWh/100 kg_{fabric})
- Initial energy use: 617.3 kW (66.8 kWh/100 kg_{fabric})

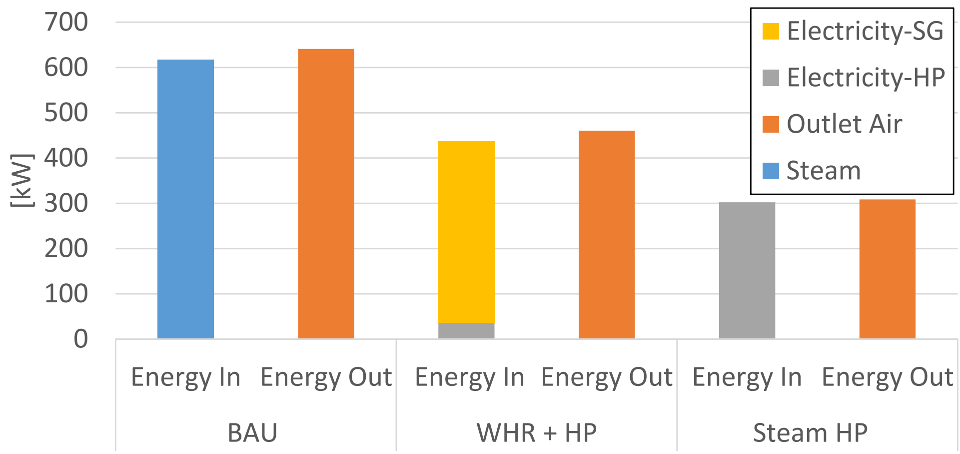
Electrification Option 2

- COP theoretical: $COP_L = 6.3$
- COP model (two stage): $COP = 1.94$

} HP efficiency 31.0 %

- HP Electricity use: 302 kW (32.7 kWh/100 kg_{fabric})
- Initial energy use: 617.3 kW (66.8 kWh/100 kg_{fabric})

Tunnel finisher
Electrification Results



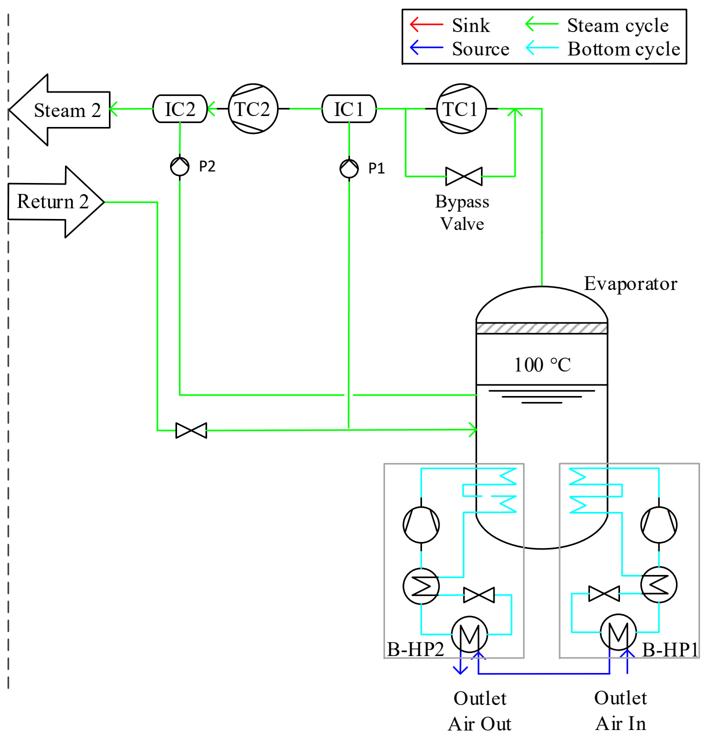
			2015	2016	2017
BAU	Steam	MWh/year	769.07	770.73	842.80
WHR + HP	Electricity	MWh/year	44.53	44.62	48.80
	Steam	MWh/year	499.23	500.31	547.10
Steam HP	Electricity	MWh/year	376.37	377.18	412.45

Central Heat pump Utility Laundry

- Collection of all exhaust air streams
- Air stream at **82 °C** with humidity of 0.061 kg/kg
- Cool down to 22.8 °C

- Supply of steam at **180 °C**
- Supply of 2.35 MW
- Condensate return 120 °C

- **COP = 1.87**
- Electricity use: 1.285 MW



Economic analysis electrification laundry
Investment costs

Central Electrification

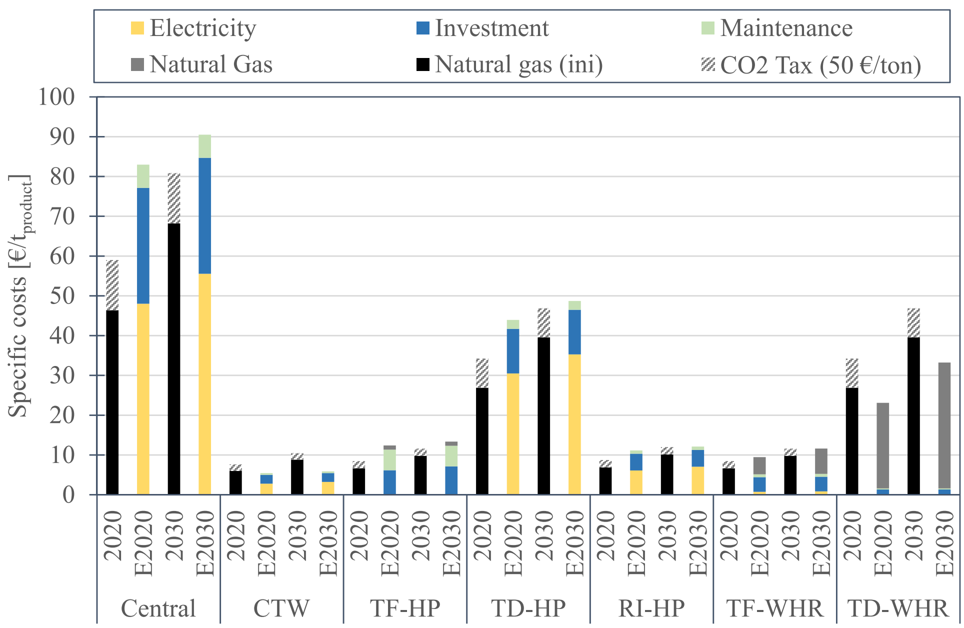
		Total Investment [€]	Specific Investment [€/kW$_{elect}$]
Utility	Central Steam HP	2,357,343	2,216
CTW	WHR + HP	180,599	786
Tunnel Finisher	Steam HP	422,285	2,454
Tubmble Dryer	Steam HP	912,428	1,671
Roll Ironer	Steam HP	343,186	1,856
Tunnel Finisher	WHR + HP	299,459	3,025
Tubmble Dryer	WHR	107,277	394

1.858.000 €

De-central Electrification

Energy Efficiency

Economic analysis electrification laundry
Specific Costs



Summary and Discussion

- Electrification through heat pump integration reduces energy use by 50 %
- Solutions where electrification is combined with energy efficiency best economics (e.g. CTW and dryer exhaust)

- Challenges in implementation
  - High temperatures and high temperature lifts
  - Condensation in heat exchanger
  - Fibers/ powder in heat exchangers

- Economic Assessment
  - Price ratio NG/EL not sufficient for most options
  - Investment costs high (afskrivning 20 år)

Ministry of Environment and Food of Denmark · DI Confederation of Danish Industry · Consulate General of Denmark Silicon Valley · State of Green Connect. Inspire. Share. Think Denmark · Danish Energy Agency

16th March 2021 - 17.30 to 18.30 PM CET

https://stateofgreen.com/en/events/decarbonizing-the-food-beverage-industry/

Thank you for your attention!

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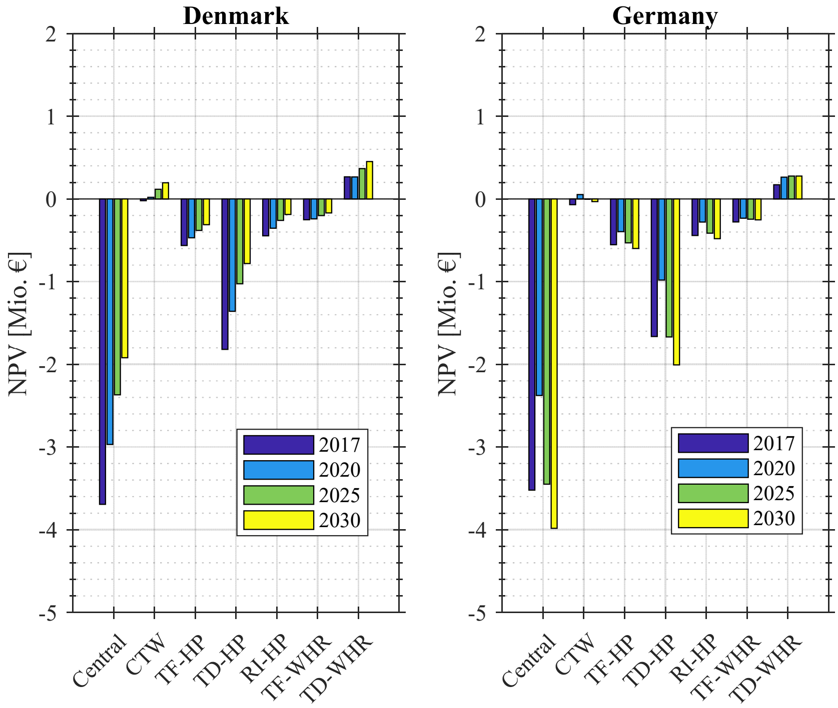
Additional Slides

Laundry Case Study

De Forenede Dampvaskerier (DFD)

Economic analysis electrification laundry
Net Present Value



Economic analysis electrification laundry
Payback Time (years)

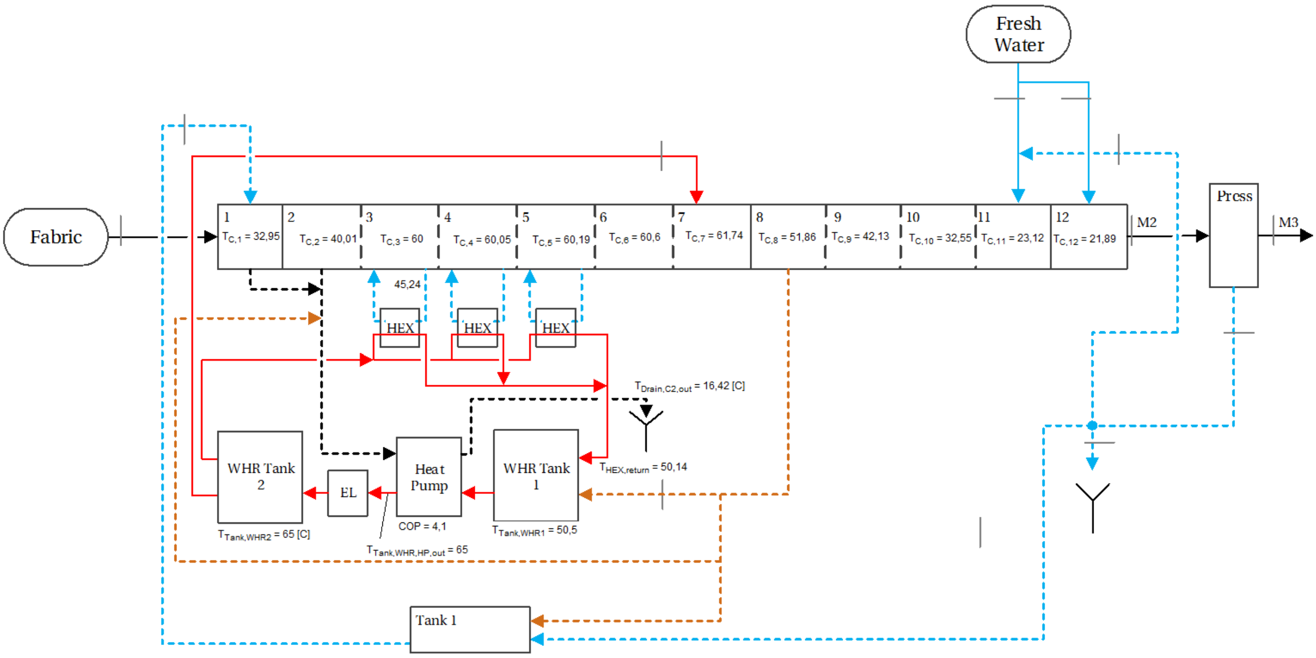
		2017	2020	2025	2030
Utility	Central Steam HP	-	-	80	41
CTW	WHR + HP	15	12	9	7
Tunnel Finisher	Steam HP	-	188	54	35
Tubmble Dryer	Steam HP	-	-	214	47
Roll Ironer	Steam HP	-	97	37	25
Tunnel Finisher	WHR + HP	45	41	31	25
Tubmble Dryer	WHR	4	4	3	3

With subsidy similar to the Energy Saving Obligation Scheme (0.05 €/kWh):

			2017	2020	2025	2030
Utility	Central Steam HP	-	-		75	39
CTW	WHR + HP		13	10	7	6
Tunnel Finisher	Steam HP	-		178	51	33
Tubmble Dryer	Steam HP	-	-		196	43
Roll Ironer	Steam HP	-		90	34	23
Tunnel Finisher	WHR + HP		43	39	29	24
Tubmble Dryer	WHR		3	3	2	2

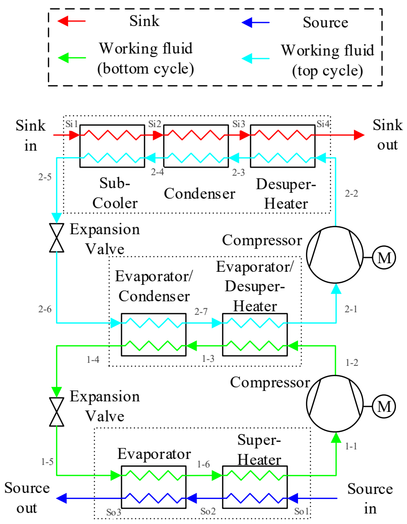
Continuous Tunnel Washer

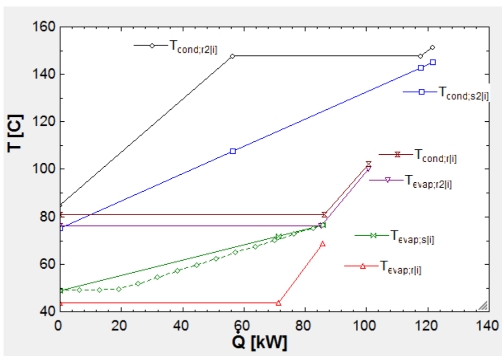
Electrification and WHR – Model results

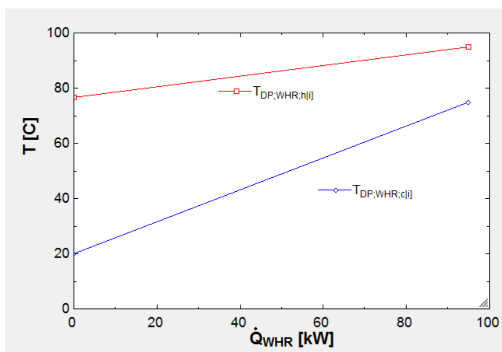


Tunnel finisher

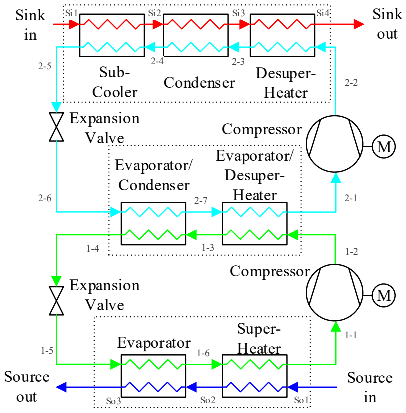
Results - Electrification Option 1

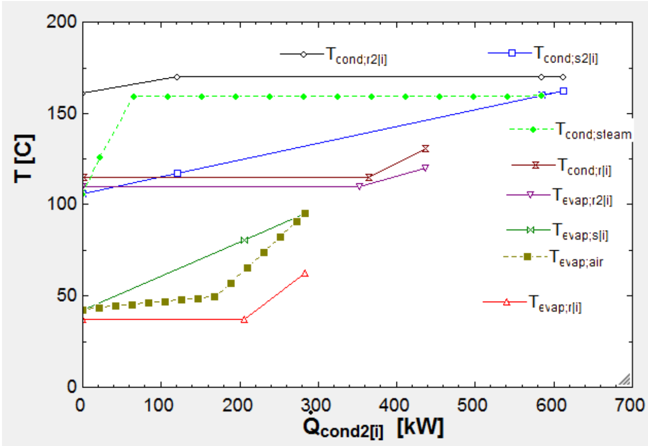






Tunnel finisher
Results - Electrification Option 2



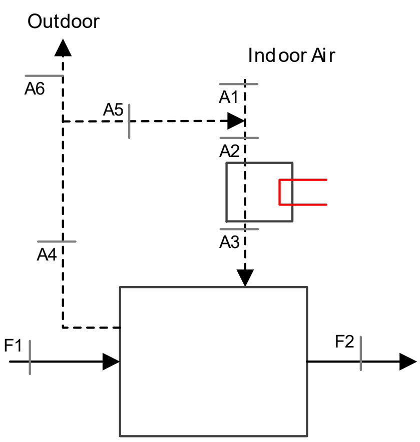


- COP theoretical: $COP_L = 6.3$
- COP model (two stage): COP = 1.94

HP efficiency 31.0 %

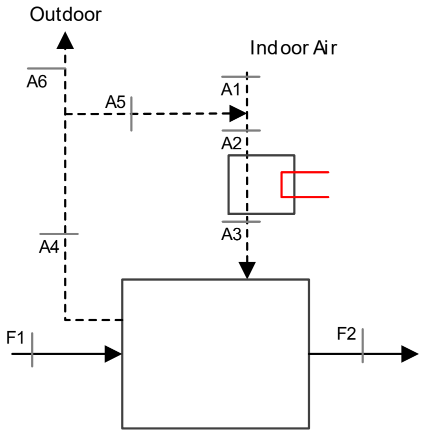
- HP Electricity use: 302 kW (32.7 kWh/100 kg_{fabric})
- Initial energy use: 617.3 kW (66.8 kWh/100 kg_{fabric})

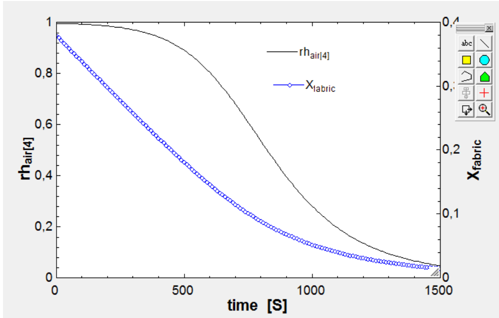
Tumble dryer
Introduction

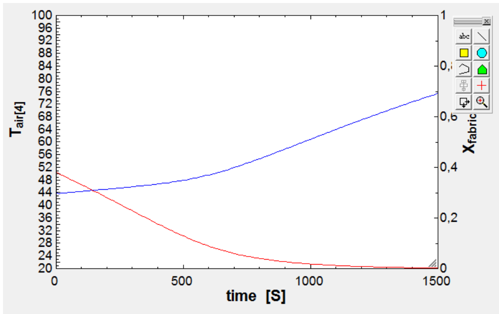


- Challenges
  - Many different dryer operating modes
  - Some literature parameters in model
  - A3 between 90°C and 180°C
- Electrification
  - WHR and HP integration directly in dryer
- Assumptions model
  - Fixed air circulation: 40 %
  - No heat losses
  - No part load considered (WHR)
- Assumptions Electrification
  - Some simplifications
  - Averaged temperatures & humidity

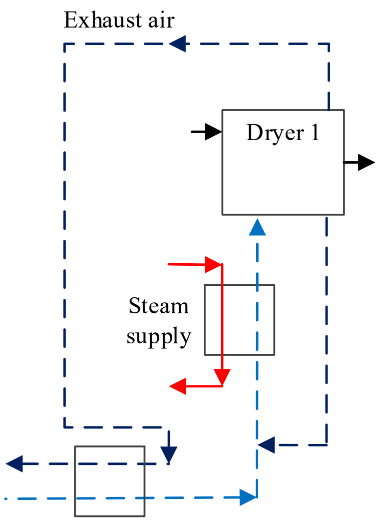
Tumble dryer
Modelling

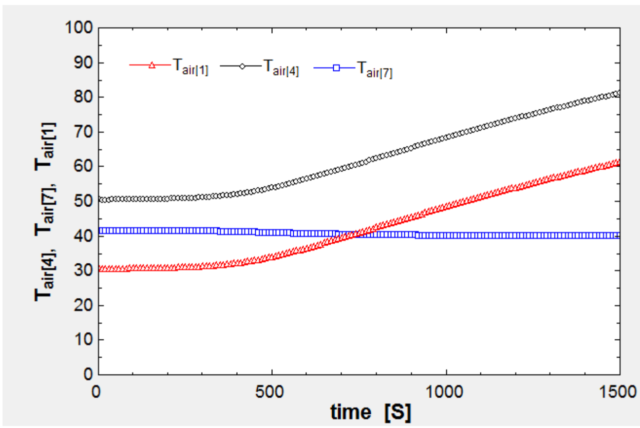






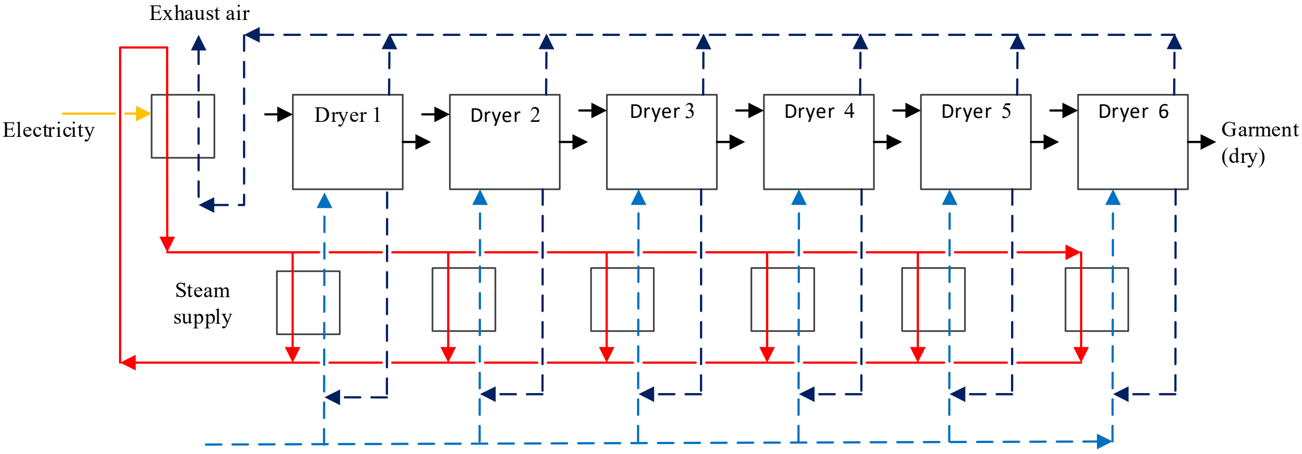
Tumble dryer
Waste heat recovery – Direct heat exchange





- Consideration of heating phase only, no cooling down (simultaneity of heating demand and excess heat)
- No part load operation of heat exchanger

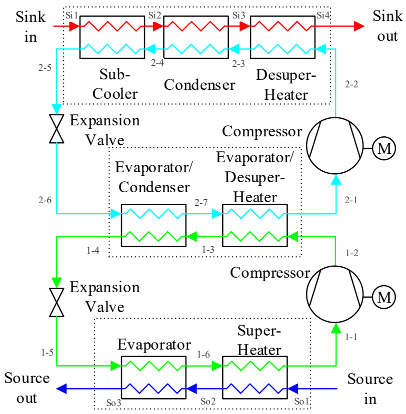
Tumble dryer
Modelling – Electrification

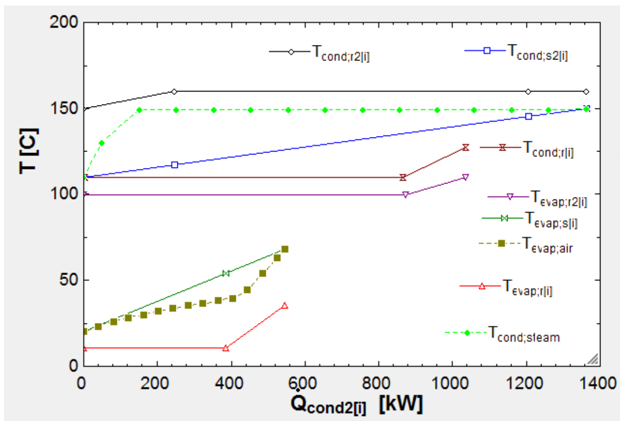


Assumptions

- Average Temperature A6: 68 °C
- Average Temperature A3: 120 °C
- Hum Ratio out – 0.050 kg/kg
- Total air flow rate taken into account (including cool down)

Tumble Dryer
Results - Electrification Option 2





- COP theoretical: $COP_L = 4.68$
- COP model (two stage): COP = 1.67

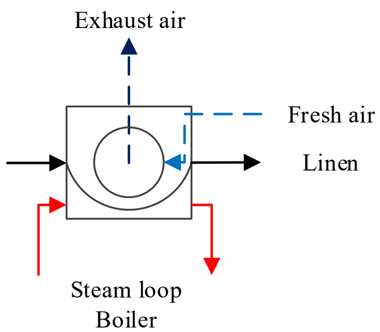
} HP efficiency 38.0 %

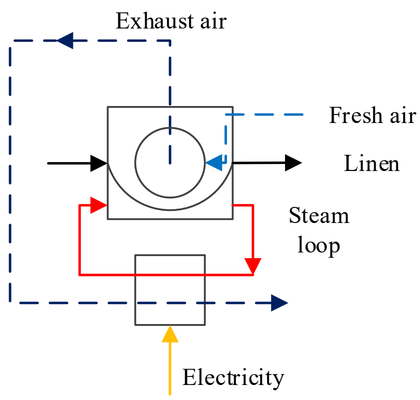
- HP Electricity use: 817 kW ($0.345\ kWh/kg_{fabric}$)
- Initial energy use: 1363 kW ($0.609\ kWh/kg_{fabric}$)

Tumble Dryer
Results - Summary

			2015	2016	2017
BAU	Steam	MWh/year	2,869	3,031	3,406
WHR	Steam	MWh/year	2,286	2,415	2,714
Steam HP	Electricity	MWh/year	2,043	2,043	2,043

Roll Ironer
Electrification

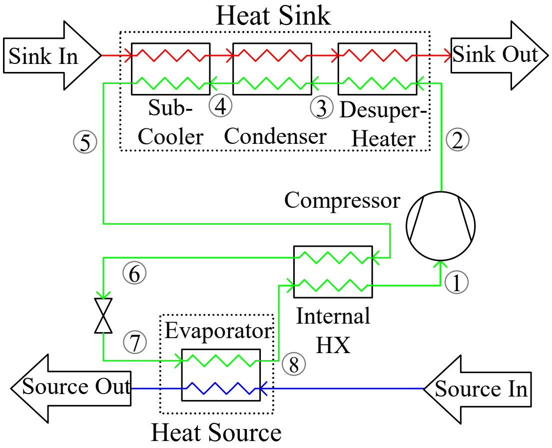


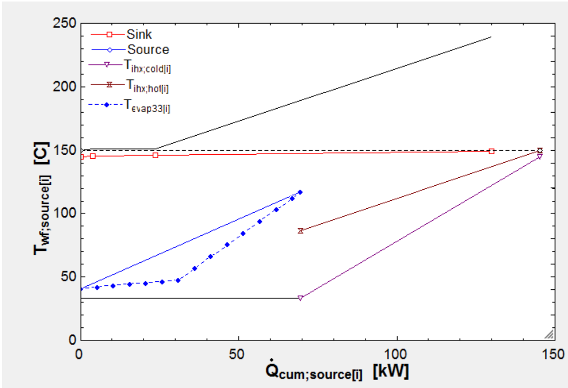


Capacity	275 kg/h
Remaining humidity	36 %
Air inflow	1500 kg/h
Air outflow	1500 kg/h
Hum air out	0.0738 kg/kg
T air out	117 C
T air in	24 C
Energy use	130 kW
Steam use	205 kg/h

- Excess heat from suction air
- Electrification options:
  - Steam generation (electric boiler or HP)
  - Electromagnetic (e.g. IR)
  - Electric heating pads

Roll Ironer
Electrification





- COP theoretical: $COP_L = 6.05$
- COP model (two stage): COP = 2.15

HP efficiency 35.5 %

- HP Electricity use: 60.42 kW ($0.220\ kWh/kg_{fabric}$)
- Initial energy use: 130 kW ($0.473\ kWh/kg_{fabric}$)

Roll Ironer
Summary

			2015	2016	2017
BAU	Steam	MWh/year	722	725	870
Steam HP	Electricity	MWh/year	336	337	404

Electrification of industrial processes with low-to-medium temperature heat demand: CP Kelco case study

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Introduction

Net zero emissions by 2050 – that is the long-term climate goal for Denmark. To reach this goal, an increase in renewable electricity production is likely to be an important action. A convenient extension to increased electricity production from renewables is electrification of the transport and industrial sector. The electrification of the production industry is an area which is not well studied and to which a general methodology is yet to be formulated.

The aim of the study was to present an approach for electrification of processes in low-to-medium temperature production industry, for which the Danish pectin production factory CP Kelco was involved as a case study. The results and experiences from an electrification analysis of CP Kelco could be used as foundation for a future general approach.

CP Kelco produces pectin and carrageenan from citrus peels and seaweed and spends around 83 MDKK on natural gas per year to heat their processes. At CP Kelco, water is evaporated to a great extent along with separation of alcohol in distillation columns by heat input from steam. Other minor heating purposes using steam such as drying and space heating also contributes to the high natural gas consumption.

The following important elements/queries were presented by CP Kelco to be investigated during the study:

- Determining the factory hot and cold utility demands by performing a pinch analysis
- Identifying the processes that can be electrified
- Determine the limits that exist for electrification strategies
- Proposing solutions that can overcome the electrification limits
- Reducing the energy demand of the plant by at least 20

The presented report is summery of a master project [1], which has been done at section of thermal energy, Department of Mechanical Engineering, Technical University of Denmark in 2020.

CP Kelco case study

The following section presents general information on CP Kelco, acting as a case study, followed by an overview of the production flow along with a brief description of the processes involved.

CP Kelco's factory in Lille Skensved is the world's largest pectin factory. The factory was built in 1947 by Karl Pedersen and sold in 1968. The factory was further sold two times and is now a part of J. M. Huber Corporation. Besides producing pectin, the factory produce carrageenan and LBG (Locust Bean Gum).

The factory operates almost non-stop throughout the year on various production lines and consumes around 34 Nm^3, 828 Nm^3, and 57 MWh Natural gas, biogas, and electricity respectively in 2018. CP Kelco operates its own CHP plant, which produces electricity and 7 bara steam for the processes. In addition, CP Kelco also delivers heat to a district heating network, owned by the company VEKS I/S. The heat delivered to VEKS is excess heat from on-site distillation columns that primarily delivers heat to Køge municipality.

Pectin is extracted from citrus peels, carrageenan from seaweed and LBG from Locust Bean seeds. The factory produces two types of pectin and two types of carrageenan.

The main processes and utilities in the production at CP Kelco are listed below:

Manufacturing processes

- Extraction
- Evaporation
- Precipitation
- Drying

Service processes

- Distillation
- Central heating
- Space heating
- CIP (Cleaning In Place)

Production utilities

- Heating of processes
- Cooling of processes

The production steps and utilities presented above are at present time already interlinked in several ways of internal heat recovery and district heating production. Therefore, alterations in utility or production technologies could have both negative and positive consequences for other interconnections further downstream. The overall product flow and the main utilities for the processes are presented in Figure 1 and briefly outlined below.

The production processes of pectin are alike, which also applies to Carrageen in between. In the extraction section, pectin is extracted from citrus peels and carrageenan from seaweed. After extraction, the product streams are concentrated in evaporation sections, where water is evaporated from the product stream. The concentrated streams then undergo precipitation. From the precipitation section, the product streams are dried to the final product.

From the precipitation section, the precipitation inhibitor has been reduced to low concentration. In addition, in the drying process, the evaporated inhibitor is absorbed in water to lower concentrations. To increase the concentration of the inhibitor from precipitation and the drying section, it is distilled in the distillation columns to reach 80 % concentration.

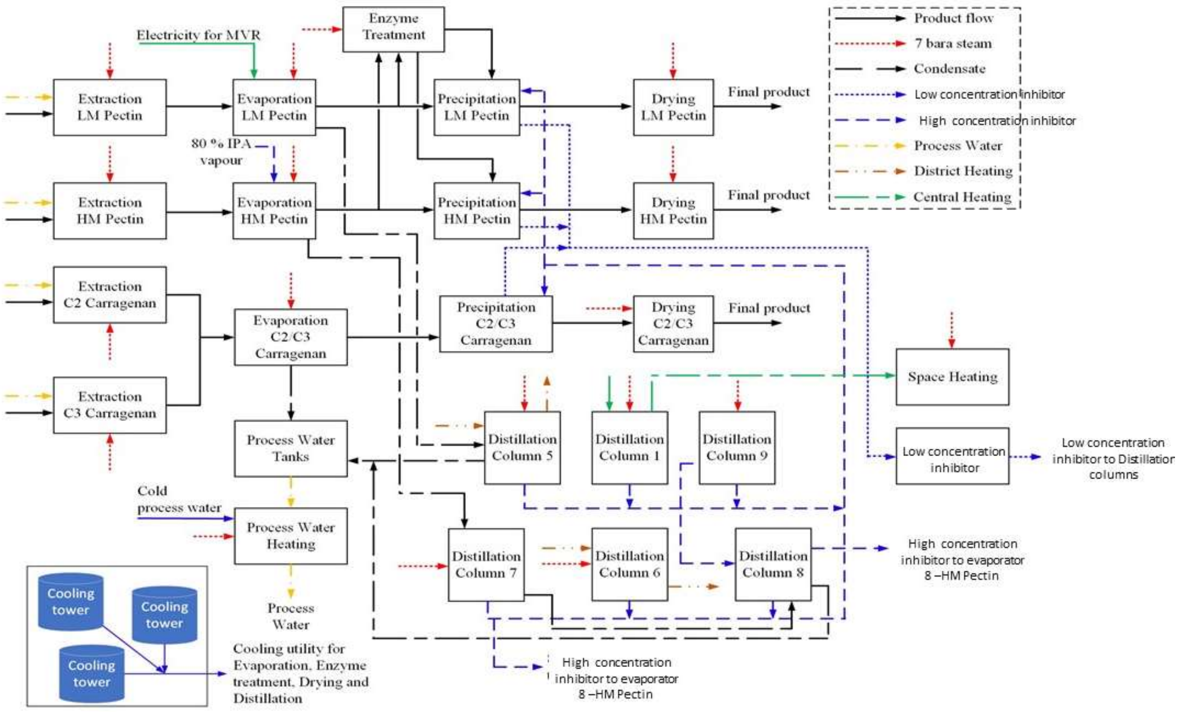

Figure-1: Product flow and utility chart for processes at CP Kelco without Locust Bean Gum production.

Methods

Electrification of production industries as both grass root and retrofit is an area highly unexplored, in terms of a general electrification methodology and approach. Therefore, this work aims to shed light on this matter, and to do so, an approach is suggested and presented in the following.

The approach suggested for successful electrification followed in this study is presented below.

1. *Energy mapping of processes*
2. *Pinch analysis*
3. *Screening of possible electrification option*

4. *Detailed energy analysis of selected electrification options*
5. *Economic and environmental evaluation of electrification cases*

The approach takes its origin in a thoroughly worked out energy mapping with high level of detail on the material streams in the processes at CP Kelco. In step 2, the material streams involved in the energy mapping are analyzed in terms of pinch analysis, to clarify the question of whether the heat integration from pinch analysis is a natural and beneficial starting point for successful electrification. In point 3, after the pinch analysis, several options for full electrification of CP Kelco are screened with regards to electricity consumption and system complexity. The electrification screening consists of cases with various technologies, for which some of the cases are compared to similar ones, including a reduction in heat consumption equal to the heat recovery potential found from the pinch analysis in point 2. In point 4, after a detailed energy analysis of the selected cases are performed, e.g. by modelling technologies to achieve more realistic and thorough results. Finally, in point 5, the cases chosen for further analysis are evaluated in terms of economy and environmentally indicators.

For simplicity reasons the processes at CP Kelco are assumed to be continuous with 8500 hours of operation per year, whereby parameters such as heat transfer dynamics and simultaneity are not taken into account. Finally, at the request of the company involved, the local CHP plant operation is modelled for further analysis of the operational expenditures.

Energy mapping

The entire work of this thesis is fundamentally based on the thoroughly performed energy mapping of CP Kelco supplied by Viegand & Maagøe AS. The energy mapping is based on the data from 2018, and it consists of mass flow rates (tonne/year), heat rates (kWh/year) and temperatures throughout the processes.

Energy analysis

All mathematical models of processes used in the energy analysis are fundamentally based on 1st and 2nd law of thermodynamics and the law of mass conservation and solved numerically. Considering a CV (Control Volume) and steady state conditions, the 1st law can be expressed with Equation (1), where changes in kinetic and potential energy are neglected.

$$\dot{W} + \dot{Q} = \sum_i (\dot{m}_{in} h_{in}) - \sum_i (\dot{m}_{out} h_{out}) \qquad (1)$$

The conservation of mass for a control volume and steady state conditions can be depicted with Equation (2)

$$0 = \sum_i (\dot{m}_{in}) - \sum_i (\dot{m}_{out}) \qquad (2)$$

Moreover, in order to find out whether the heat integration methods such as pinch analysis, is beneficial to implement prior to electrification or if heat integration dilutes the full potential of electrification. A Bottom-up methodology for electrification acted as a point of reference followed by the modernized method of the Specific Savings Potential method (SSP). Finally, it was identified how alternative process technologies could cause radical improvements in terms of energy and economical savings.

Electrification approach for the case study

The electrification analysis of CP Kelco is carried out by first proposing 8 different electrification cases with different technologies (available on the market or to a certain extent also theoretical technologies of upcoming potential) to undergo a screening process. These cases are investigated with respect to total electricity consumption on a low level of detail. Secondly, three of the best performing cases are picked out based on a combined assessment of the case electricity consumption, complexity of the technologies and expected investment cost. Lastly, a detailed energy analysis of the selected cases are performed with economic and environmental results as main objectives.

The main steps to perform in the proposed general electrification approach are:

(1) Replace inefficient technologies with alternative technologies for energy savings, if feasible
(2) Identify most favorable utilization of heat pumps
(3) Identify alternative technologies for utility demands out of reach of state-of-the-art heat pumps.

The technologies, which have been considered for the electrification cases, are as follows:

- Heat pumps: central steam generation heat pump for steam consumption and local heat pumps with central heat recovery loop for covering the cooling and heating demand below 80 °C
- Mechanical vapor compression technology (MVR) for evaporation and distillation
- Biogas engine: for electricity production and space heating
- Electric boiler: for steam production

From the three selected cases:

Case A: consists of a cascade heat pump with a multi-stage R-718 cycle for steam generation and local heat pumps to cover cooling and heating deman.

Case B: is similar to case A, with the only difference of including MVR technology in the full range of evaporation sections.

Case C: is chosen for further investigation and consists of MVR on the full range of evaporation sections and distillation columns, where the remaining heat demand was covered with local heat pumps and electric boilers.

The first two cases (Case A and B) obeyed a current district heating production agreement of the factory. Case C assumed the factory to leave the district heating agreement when possible, whereby the electrification strategy was split into 4 steps, starting from year 2020 to 2045 with a time domain of every 10 years. All steps were assumed to have a 20 year lifetime starting from the year of implementation. Figure 2 and 3 illustrates the two cases of A and C.

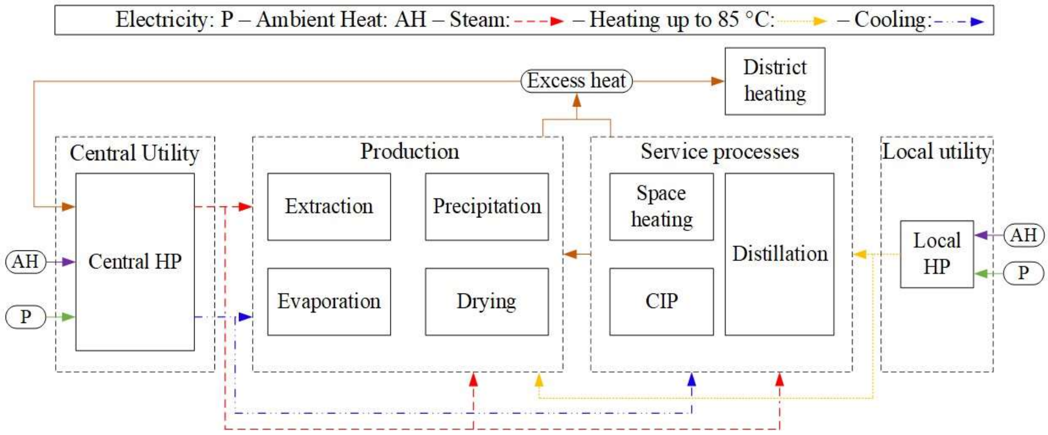

Figure 2- Case A with central steam generation heat pump and local heat pumps.

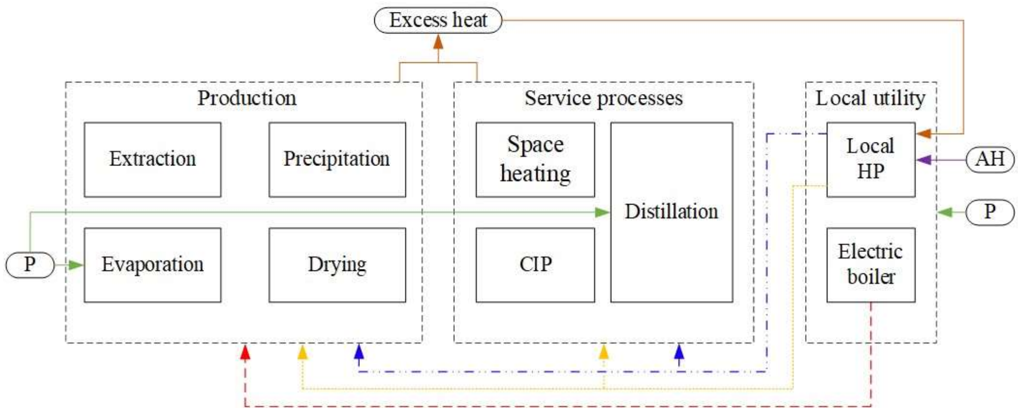

Figure-3: Case C with local heat pumps, local electric boilers and MVR on evaporation and distillation sections.

Economic analysis

Before any project is to be realized, an economic assessment needs to be performed. If the project proves to be economically feasible the project can be realized, on the other hand if it is not feasible the owner will not invest. Several factors are required, such as the total investment cost and the revenue generated by the project. Lastly, economic indicators for the economic assessment needs to be determined.

Environmental analysis

The environmental analysis is based solely upon reduction in CO_2 emission. The CO_2 emission of natural gas is assumed constant to a value of 205 g/kWh [2]. The CO_2 emission of electricity varies a great deal based on the energy conversion process. In this work the EU reference scenario 2016 [3] will be used as forecast for CO_2 emission of electricity. The analysis includes emissions for Denmark and EU-28 in the period 2020-2039.

Results

This chapter presents the most important results from the case study at CP Kelco. First, the results and analysis of the energy mapping of CP Kelco, traditional and Specific Saving Potential (SSP) pinch analysis will be presented. Afterwards, the results from the electrification approach are presented followed by the economic and environmental results.

Energy mapping and pinch analysis

The energy mapping of the production processes showed that the highest temperature demand is 120 °C, with 40 % of the energy use below 80 °C. Furthermore, analysis of streams using the traditional pinch analysis showed a location of the pinch point at 77.7 °C with a hot and cold utility target of 28.4 MW and 4.6 MW respectively. Fulfilling the entire potential of internal heat recovery estimated from pinch analysis can lead to 25% reduction of the overall heat demand of the factory. The SSP method identified 4 feasible matches of material streams. The total heat recovery of the 4 matches summed up to around 12 GWh per year equal to yearly savings of around 2.55 MDKK with PBT on investments of maximum 2.1 years.

As the matches do not generate revenue if either of the two streams is not in operation, the obtained results for the pinch matches only applies to a situation, where a contemporary factor of the processes involved is 100 %.

Electrification of CP Kelco

The total energy use based on electricity of case A, B and C was found to be 166 GWh, 138 GWh and 114 GWh respectively, which equals a reduction compared to business as usual (BAU) of 32.6 %, 50 % and 69 %. In case A and B where cooling and steam is supplied to the factory from the central heat pump system, the Coefficient of performance (COP) of such system reaches 2.3 and 2.4 respectively. In case C, the overall heating COP for local HP's was 3.1.

All of the cases had a positive NPV (Net Present Value). The TCI (Total Investment Cost) of the technologies involved in case A and B was found to be 186 MDKK and 223 MDKK with a simple payback time of 7.3 and 6.2 years respectively. The NPV was found to be 232 MDKK and 322 MDKK for a 20 year lifetime of case A and Respectively. The calculation of NPV for a 20-year lifetime, considering subsidies, showed feasible investment of cases A and B. Also, the environmental aspects for the two cases (A and B) showed approximately 66 kt/year reduction of CO_2 emission in the final year of the project life time.

The total consumption of natural gas and electricity from BAU to full electrification in 2040-2045 for the case C is depicted in Figure 1.

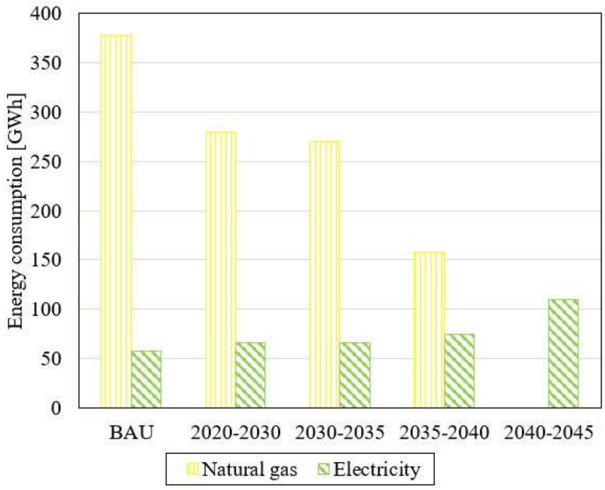

Figure-1: Development of energy use from BAU to full electrification in case C, at CP Kelco

The NPV equals to 201 MDKK, 54 MDKK, 250 MDKK , and 95.6 MDKK and the payback time of 3.7 years, 2.9 years, 3.4 years , and 3.9 years respectively for the time domains of case C, presented in Figure 1. The environmental impact of implementing case C with a final yearly CO_2 emission of approximately 7 kt/year equal to a reduction of 70 kt/year.

In addition, the results showed that investigating alternative technologies down to process level such as MVR can be highly beneficial. In case C, the energy use of the evaporation process is around one seventh of the steam consumption in BAU or equal to an energy reduction of 86 %, and in distillation column, as the largest energy consumer in BAU, a reduction of 93% of the energy demand can be obtained, with full electrification in 2040-2045.

General approach for electrification of low-to-medium temperature production industries

The following aims to present the recommendations and guidelines for a general electrification of low-to-medium temperature processes to aid companies towards electrification. This will partly be based on experiences obtained through the work of the CP Kelco case study presented above, but also general knowledge obtained throughout the project and from literature.

One of the main learnings from working with the case study is the complexity of large-scale production facilities. This was found e.g. by the replacing of steam driven distillation with MVR distillation, which induced external heating demand for process water. This also led to the learning that alternative technologies could have an overshadowing influence on how the electrification is executed to obtain the best solution of economy and environment. Once again shown by the case with MVR on distillation and evaporation sections that made up for the far highest energy savings.

The learnings were used to establish an approach to electrify low-to-medium temperature production industries where heat pumps play a central role as explained by Figure 2. The approach also question whether heat integration prior to electrification is advantageous or not.

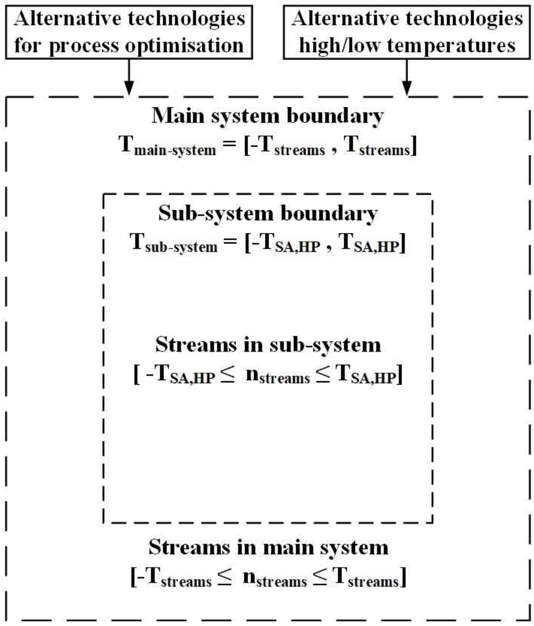

Figure-2: System boundaries of electrification strategy including sub-system boundaries for state-of-the-art heat pump temperature limitations

Firstly, the entire production facility of material streams, referred to as main system in Figure 2 are review in light of AT's (Alternative Technologies). This is done to anticipate the possibly large energy savings from replacing old or inefficient technologies with new and efficient ones, whereby the low-hanging fruits of energy savings are picked first.

Afterwards, a sub-system of material streams is defined based on operation temperature limits of SA (State-of-the-Art) heat pumps. The sub-system is investigated in terms of whether heat integration via traditional pinch analysis or modern pinch analysis such as the SSP method is favorable for subsequent integration of heat pumps to cover minimum energy requirement. In addition, a system of heat pumps should be designed to cover all material streams in the subsystem, to compare the electricity consumption with the system where heat integration is involved.

Independent of the outcome of the latter analysis, the main system might operate at temperatures outside the boundaries of state-of-the-art heat pump temperatures defining the sub-system, why alternative technologies should be considered to cover the heating and cooling demand at such temperatures.

The above presented boundary systems and the brief explanation of the approach to implement electrification via heat pumps and alternative technologies is presented in details in Figure 3.

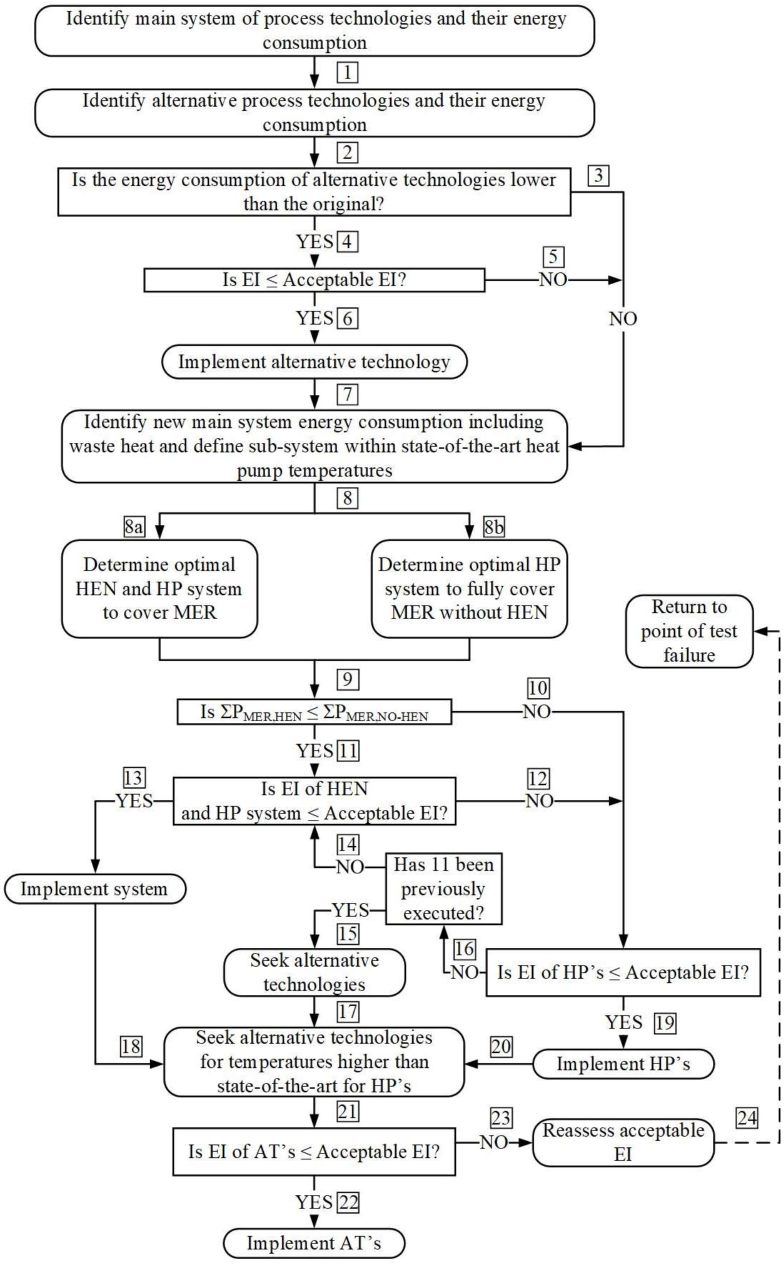

Figure-3: Suggestion for general electrification approach for low-to-medium temperature processes in production industries.

A successful electrification project takes the same origin as a successful pinch analysis, as a thoroughly performed energy mapping through the identification of the overall system process technologies and material streams temperature targets are essential. This also acts as the starting point for this procedure.

Once the energy mapping is performed, AT's for the processes involved in the main system should be investigated and identified and afterwards analyzed in terms of energy consumption as in step 2. This step would likely be done via, consultants, experience from the industry or contact with equipment suppliers.

If the AT's identified have lower energy consumption and the investment is feasible rated up against an EI (Economical Indicator) subjective to the company involved, the investment should be undertaken and the technology implemented. Reversely, if the energy consumption of the AT is higher than the current technology, or it simply fails based on the economical indicator, the AT identified should be discarded, leading to step 5.

In step 7, the potentially new system of technologies and material streams including waste heat recovery potential is identified along with a sub-system operating within the boundaries of the state-of-the-art temperatures of heat pumps.

This further leads to step 8 that splits into two tasks. In 8a an optimal HEN is defined, along with the resulting reduced MER of the sub-system. This can be done in different ways, e.g. by traditional pinch analysis or the SSP method. The MER determined from the targeting procedure is to be covered by heat pumps for which the total electricity consumption is determined.

In point 8b, an optimal system of heat pumps is designed and analyzed, covering the full cooling and heating utility of the processes in the sub-system. The heat pumps operate at various COP and capacities e.g. by the means of cooling loops, which provide cooling to the processes and acts as heat source for the heat pumps. The electricity consumption of such heat pump system is thus determined, leading to the next step in the approach.

In step 9, the total electricity consumption of the heat pumps covering the reduced MER in step 8a is compared to the electricity consumption of the heat pump system covering the full utility demand of all material streams in step 8b. If the Benchmark of the two scenarios shows a lower electricity consumption for the scenario of step 8a, the feasibility of the HEN and matching heat pump system is assessed in terms of an EI in step 11. If the EI is complied with, the systems of both HEN and heat pumps are implemented in step 13. If the EI is not complied with, the feasibility of the heat pumps system from step 8b is assessed. If the system from 8b also turn out infeasible, one should seek alternative technologies in step 15.

If the heat pump system from step 8b shows lower electricity consumption than the system in step 8a, the procedure follows step 10 to assess the feasibility of the heat pump system. If the feasibility of the heat pump system complies with the EI, the heat pumps are implemented in step 19. If the heat pumps on the other hand are not feasible, the procedure follows step 14, and the feasibility of the HEN and matching heat pump system is assessed. If the system from 8a is feasible, step 13 is followed and the system is implemented. Should the system prove infeasible step 15 is considered.

Common to all outcomes from above, is when the MER of the sub-system is covered, one should seek alternative technologies to cover the temperatures lower or higher than the sub-system boundaries in step 17, 18 or 20. If the alternative technologies identified are feasible, they are implemented which ideally results in the entire production facility to be electrified in point 22. If the AT's fail the feasibility test, the procedure follows step 23 where the limits of the economical indicator should be reassessed, where after one should continue the procedure at the point of failed feasibility test.

Conclusion

This study investigated the potential for energy and economical savings in electrifying industrial processes of low-to-medium temperature, by drawing up concrete scenarios in a case study, to cover the energy demand at CP Kelco a large-scale factory producing pectin.

The Study showed that with full electrification of CP Kelco the total energy use is reduced by approximately 70 % and CO_2 emission by 90 % in 2045. In addition, the analysis also showed that it is not always beneficial to perform a pinch analysis and implementing a heat exchanger network before initiating an electrification plan. Furthermore, it was clear that other factors might constrain the electrification possibilities. Specific to CP Kelco, the district heating agreement stood out as a limitation for successful electrification with heat pumps. This is an important lesson learned, which other companies can benefit from, as excess heat should preferably be utilized within the factory boundaries.

The electrification may well be a necessary step to take both in an environmental perspective but also from political perspective if Denmark wishes to achieve net-zero emission before 2050. In addition, it can improve the 'green profile' of the company which are of increasingly importance for companies nowadays

The work has led to insight in fields of the electrification, impacted by barriers for successful investments. It was found that the electricity to natural gas cost ratio plays key role in successful electrification if the BAU conditions are based on natural gas combustion. Moreover, the total investment cost of electrical driven technologies such as heat pumps and MVR tend to be high, which might become a challenge in the transition period, if the BAU conditions are already energy efficient.

Acknowledgment

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Viegand Maagøe

Welcome

Electrification at CP Kelco

Viegand Maagøe

Background

Experience from the industry

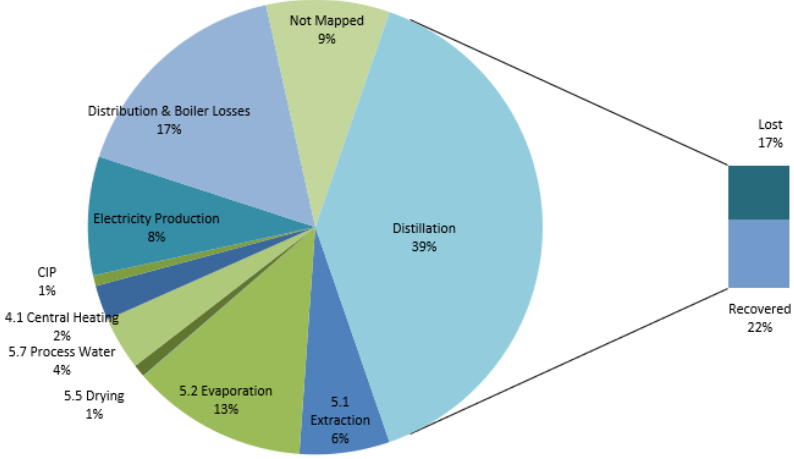
- CP Kelco in Lille Skensved is owned by J. M. Huber Corporation
- A traditional manufacturing site
- Pectin and Carrageenan production from citrus peels and seaweed
- Wide span of processes such as extraction, evaporation, precipitation, and distillation
- CP Kelco is a large consumer of primary energy such as natural gas and electricity
- CP Kelco is registered in EU ETS

Viegand Maagøe

What is CP Kelco?

Experience from the industry

- Traditional thermal powered factory
- Energy consumption in 2020:
  - Natural gas: 412 GWh
  - Biogas: 4 GWh
  - Electricity: 56 GWh
- Heavy processes are particularly relevant to electrification
- Other production sites around the world → Process optimisation and electrification might become essential
- Great willingness, interest, and focus on staying ahead of future emission targets



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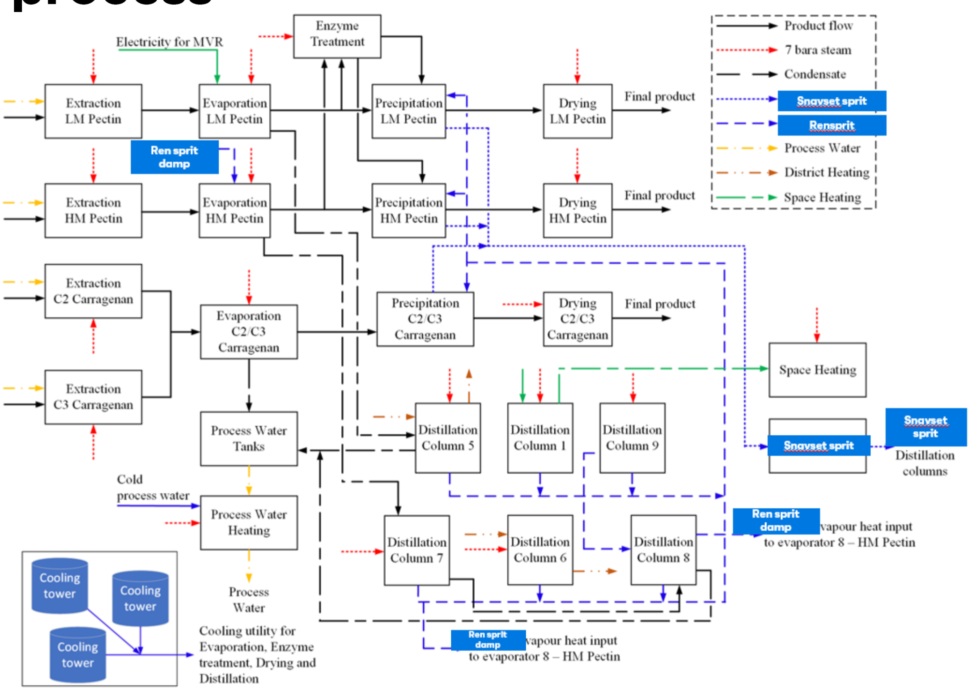
A highly integrated process

Experience from the industry

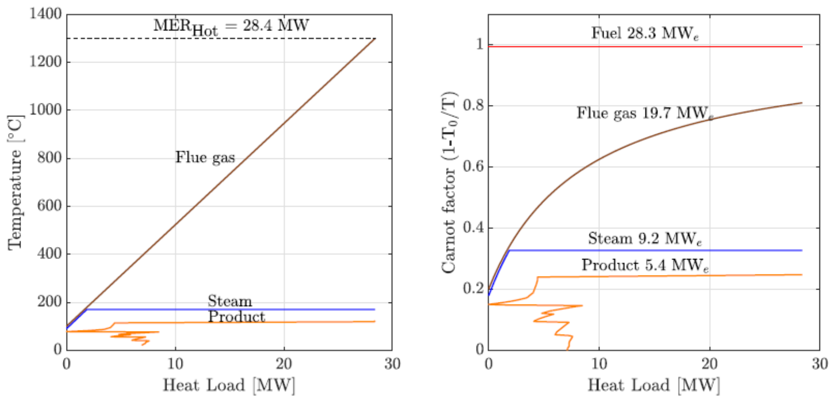
1. Manufacturing processes
   - Extraction
   - Evaporation
   - Enzyme treatment
   - Precipitation
   - Drying
2. Service processes
   - Distillation
   - Process water heating
   - Space heating
   - CIP (Cleaning In Place)
3. Thermal utility for processes
   - Steam
   - Cooling towers



Understanding levels of temperature

Experience from the industry

- Highest temperature demand is 120 °C, 40 % of the energy consumption is below 80 °C
- Great losses from combustion, steam generation, transmission, and heat exchanging with processes
- Large difference between the potential of primary energy usage and the real demand at the processes
- Electrification might be a beneficial solution

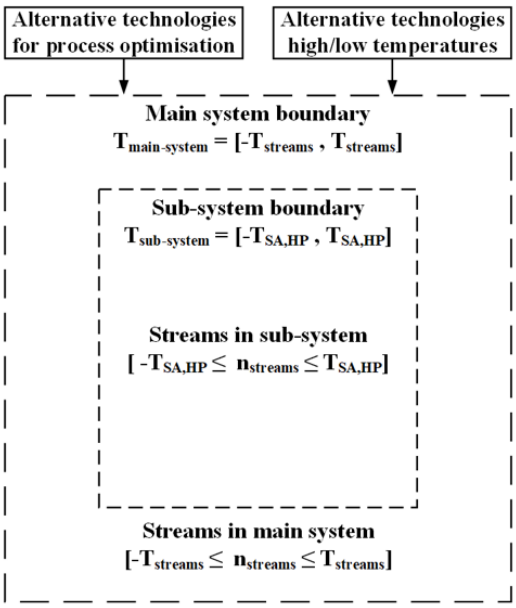


(a) Energy basis (b) Exergy basis

Electrification method

Experience from the industry

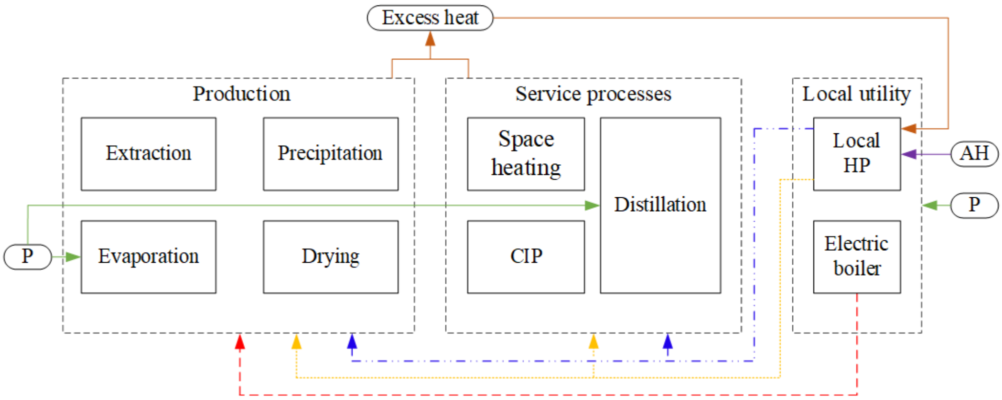
- Main system – and sub-system boundaries
- Process integration before electrification should not necessarily be prioritized
- Alternative technologies should be investigated for the entire site
- Remaining product streams are analyzed for state-of-the-art potential of heat pumps in various scenarios
- Estimation of synergy potential for heat pump integration



The electrified case

Experience from the industry

- Electrification in steps
- Alternative technologies: MVR for evaporation and distillation
- Local heat pumps with central heat recovery loop
- Electric boilers to supplement processes in need of steam
- Biogas for electricity consumption and space heating

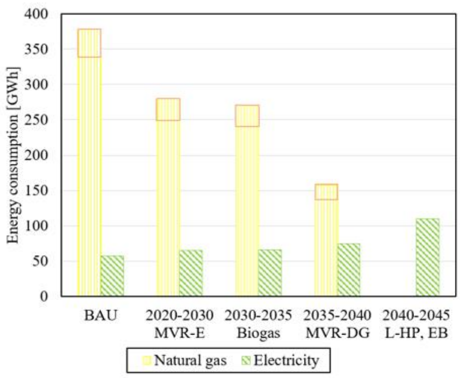


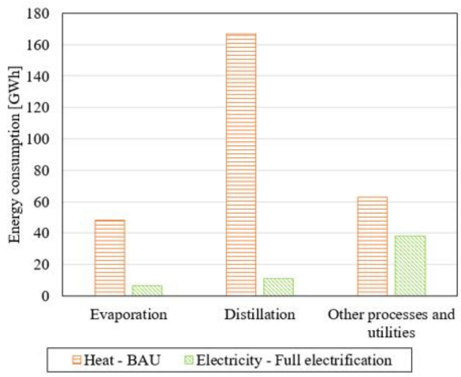
Potentials found from electrification

Experience from the industry

- Large energy savings from alternative technologies: (Evaporation and distillation)
- Biogas generates more electricity and space heating in the future
- Local heat pumps and electric boilers secure the complete electrification
- A precondition for the case is to shut down district heating production

COP of local heat pumps of 3,1 from waste heat recovery loop around the factory





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Energy consumption is reduced by approximately 70 % and emissions by 90 %, with a CAPEX of upwards of 600 MDKK

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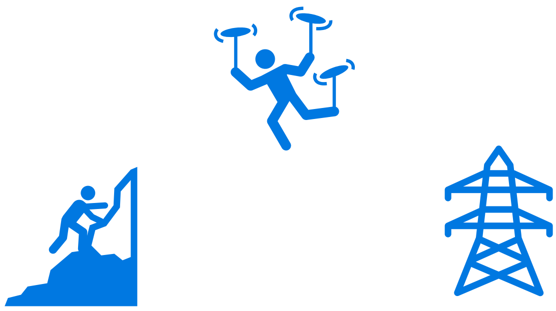
Possible barriers learned from CP Kelco

Experience from the industry

- Highly integrated processes increases the scope and investment for each project
- DH production reduces the potential in utilizing waste heat as heat input for heat pumps
- Large fluctuations in heat demand → potentially problematic to electrification
- Process integration after complete electrification
- Pre-studies of electrification are expensive: energy mapping, analyzing and developing of strategies etc.



Thanks

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Energy Optimization and Electrification Study of a Brewery, Harboe

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Introduction

The industry sector has an important role to play, if the goals of the Paris Agreement are to be met. The sector is currently heavily relying on the combustion of fossil fuels. As the electricity mix continues to rely more on renewable energy sources, transitioning towards using electricity as the main energy carrier in industries, would significantly reduce CO_2 emissions. However, the area is not yet well studied and a general methodology is still to be formulated.

The aim of the study was to investigate the potentials for energy optimization and electrification strategies for electrification of the processes in low-to-medium temperature production industry, for which the Danish brewery Harboe was involved as a case study. The results and experiences from an electrification analysis of Harboe brewery could be used as foundation for a future general approach.

The Harboe brewery is currently ranked as the third largest brewery in Denmark. Harboe uses about 34 GWh natural gas to produce the steam for hot utility systems.

The presented report is summery of a master project [1], which has been done at section of thermal energy, Department of Mechanical Engineering, Technical University of Denmark in 2020.

Harboe Case study

This section presents the Harboe brewery, which has been used as a case study followed by an overview of the production flow along with a brief description of the processes involved.

Harboe is a family owned company that was founded in 1883 in Skælskør, Denmark. Today, the company has three production facilities located in Denmark, Germany and Estonia, respectively. Harboe sold a total of 5.9 million hectolitres of beer, soft drinks and malt wort products in 2018/19 that are marketed in more than 90 countries worldwide [2] with a total revenue of 1,338 mio. DKK. The two biggest markets for Harboe are Germany and Denmark contributing 40% and 26% of the total revenues, respectively [2].

The presented study only considered the original brewery located in Denmark. The facility produces a large range of beers, soft drinks and malt extract products. The latter is a thick juice that is sold to food and beverage industries as an ingredient. Harboe is one of the world's leading suppliers of malt extract [3].

The brewery is producing all days of the week, 16 hours/day during the weekdays and 8 hours/day during the weekends, with continues processes such as fermentation. The utility system at the brewery is entirely supplied by natural gas and electricity with the amount of 34 GWh and 15 GWh respectively.

Figure 1 presents a simplified block diagram of the process at Harboe brewery.

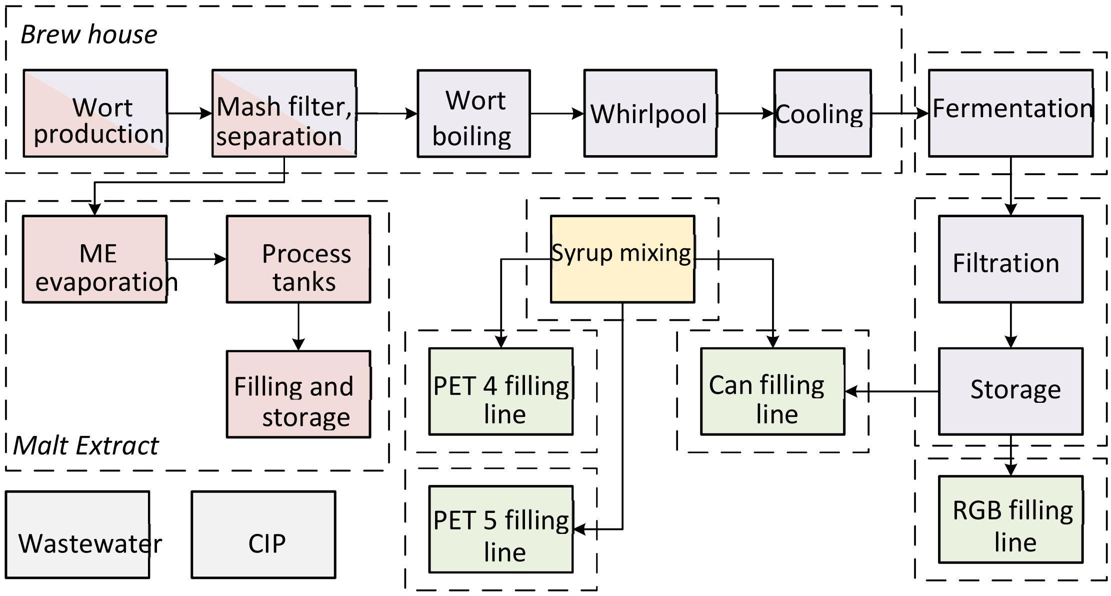

Figure-1: Simple block presentation of the processes at Harboe brewery

A description of the processes within each part of the brewery, illustrated in the Figure 1, is briefly explained below.

Beer is the main product of Harboe. Brew house is where most of the processes take place. It consists of processes such as wort production, mash separation, boiling, filtration in the whirlpool and finally cooling before the wort is sent to the fermentation tanks. After being cooled, the wort is sent to fermentation tanks and then through a filtration system before being stored in pressurized storage tanks awaiting filling. The CO_2 gas is collected and sent through a purification system before being re-added to the beer again during the final adjustments.

An important part of the heat integration in the brew house are two warm water tanks of 150 m^3 each. The tanks primarily recover heat during the cooling process after the whirlpool at 80 °C. This water is then mixed with 8 °C water before the wort production, to produce 50 °C water. Additionally, the tanks supply water to the mash filters at 80 °C and are being used to flush the system after each brew. In the weekends, the water content in the tanks is emptied and used for CIP in the brew house. The tanks can also draw 60 °C water from the malt extract condensate or in the worst case scenario 8 °C raw water which are then heated to 80 °C.

In the case of producing malt extract, the wort is sent to a specific malt extract department after the mash filter, presented in Figure 1. Similar for both types of malt extract, they are sent through a heat exchanger with 60 °C condensate on the other side that either heats up or cools down the wort. Afterwards, the wort can then be heated up with steam to the desired feed in temperature of 75 °C in the evaporator. The condensate is used to supply the warm water tanks in the brew house when necessary. The concentrate is sent to the malt extract process tanks.

The production of soft drinks is very simple and does not involve any heating or cooling.

In all the filling lines the product goes through a pasteurizer, which first heats up and then cools down the product, to remove any harmful bacteria left in the beer/soft drink. Afterwards, the product is filled into the respective container.

The brewing industry is recognized as one of the largest industrial users of water. A large amount of water is used for brewing, cleaning and cooling processes at all times around the brewery. For the Harboe case, the water in the sewer is sent to a wastewater treatment facility next to the brewery which first through a physical treatment for removing any solid materials, then through a chain of chemical treatments, finally a biological treatment.

Methods

The methods used throughout the work of this thesis are presented in the following chapter. First, the methods used during the energy system mapping are described. Next, the process integration methods are presented, explaining how the traditional pinch analysis and the ESD method were applied. After this follows a description of the approach for setting up the electrification analysis and the scenarios. Finally, the methods used for the economic and environmental analysis are presented.

Energy mapping

The entire energy system of the Harboe brewery was mapped using production data from 2019. A previous mapping of the system, carried out by Viegand Maagøe AS in 2016, was received and updated with the 2019 data. Additionally, parts of the system were changed to more accurately represent the actual system or due to new energy, recovery measures taken at the brewery. The main focus was the mapping of the thermal processes, but the electricity consumption should also be analyzed.

For simplicity, continuous operation with 4992 hours of operation per year rather than batch operation has assumed for the calculations.

Energy analysis and process Integration

All mathematical models of processes used in the energy analysis were based on 1st of thermodynamics and the law of mass conservation and solved numerically. Considering a CV (Control

Volume) and steady state conditions, the 1st law can be expressed with Equation (1), where changes in kinetic and potential energy are neglected.

$$\dot{W} + \dot{Q} = \sum_i(\dot{m}_{in} h_{in}) - \sum_i(\dot{m}_{out} h_{out}) \qquad (1)$$

The conservation of mass for a control volume and steady state conditions is presented in Equation (2)

$$0 = \sum_i(\dot{m}_{in}) - \sum_i(\dot{m}_{out}) \qquad (2)$$

In addition, in order to obtain a better understanding of the energy targets at the brewery and to investigate the effects of implementing process integration measures before carrying out the electrification analysis, potentials for process integration within the system were investigated. The process integration applied conventional and more recently developed pinch analysis tools such as Energy-Saving Decomposition (ESD) method.

Since the brewing process at Harboe runs as a batch process and not a continuous process, this complicates the overall use of pinch analysis. The Time Average model (TAM) has been applied [4] for handling batch process. The TAM approach uses average heat loads of the process operations. This approach therefore had an impact on the heat loads of the process streams, since a lot of processes have less annual production hours than the entire facility.

Electrification approach for the case study

The electrification analysis of Harboe was carried out by first proposing 6 different electrification scenarios with different technologies (based on available technologies and through a literature review of upcoming technologies with potential) to undergo a screening process. These scenarios included three different technologies, and for each technology a scenario with and without internal heat recovery was considered. This allows the analysis to evaluate whether using the wastewater through direct internal heat recovery performs better than upgrading the heat with a heat pump. A set of screening criteria were defined in order to choose the best performing scenarios for further investigation. Two general decision parameters used for evaluating electrification scenarios in the screening phase were:

- Energy consumption: first, the scenarios are screened in terms of electricity consumption, and cases with lower electricity consumption are prioritized.
- Annual savings: next, the scenarios are screened in terms of the annual savings they achieve in the first year of operation. The investment cost of the different scenarios is expected to vary a lot, so by analyzing the annual savings, the goal is to estimate how the scenarios compare in terms of allowed investment.

The chosen scenarios (3 out of 6) were then evaluated in terms of their thermodynamic, economic and environmental performance.

The technologies, which have been considered for the electrification scenarios, were as follows:

- Central electric boiler to produce steam for the heating processes
- Centralized heat pump system using excess heat and ambient heat sources to supply process heating
- Decentral system of heat pumps, electric heaters and boilers to provide heating and cooling locally where it is needed.

The three following scenarios were selected from screening analysis for further investigation. Figure2 illustrates the overall utility and production structure of business as usual (BAU) and selected scenarios A, B and C.

- Scenario A: Central electric boiler (EB) with heat exchanger network(HEN)
- Scenario B: Central heat pump (CH) with the HEN
- Scenario C: Decentral system (DS) without the HEN

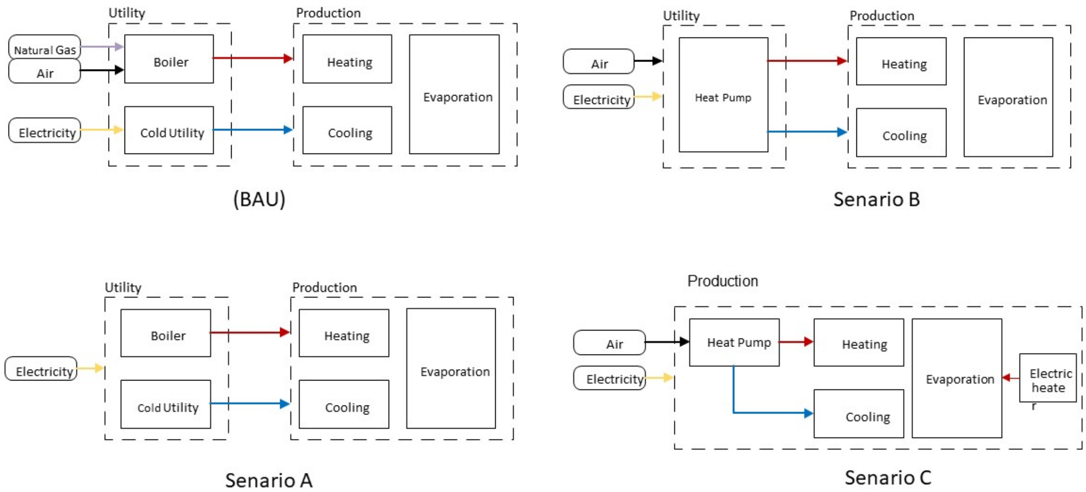

Figure-2: the overall utility and production structure in business as usual (BAU) and selected scenarios A, B, and

Economic analysis

In order to evaluate the feasibility of the developed projects, an economic analysis was carried out. This was done for both the process integration analysis and the electrification analysis. However, the level of detail varies for the two. Several factors were estimated such as the total investment cost (TCI) and the revenue generated by the project. Finally, the performance of the projects were evaluated in terms of Net Present Value (NPV) and Payback Times (PBT).

Environmental analysis

An environmental analysis of the electrification projects was carried out, to evaluate the environmental performance of the proposed projects compared to business as usual (BAU) scenario. This analysis was solely based on analyzing the CO_2 emissions from the facility.

The emission factor of natural gas was assumed to be constant over the entire lifetime and was set to 0.204 tonnes CO_2/MWh [5]. The CO_2 emission factor for electricity varies greatly depending on the electricity generation technology. However, it is the central factor of this part of the analysis, since electrification implies that on-site emissions are shifted toward off-site emissions. Therefore, it also varies a lot from country to country based on their electricity generation mix.

The analysis of the study includes both emissions from Denmark and an EU average The CO_2 emissions from electricity were found from [6] using the EU-28 reference scenario in the period of 2020 to 2050.

Results

This chapter presents the most important results that have been obtained from the Harboe case study. First, it presents the results of the energy mapping of the system followed by the results of the process integration study utilizing traditional pinch analysis and ESD method. Finally, it presents the results of the electrification analysis.

Energy mapping and pinch analysis

The energy mapping of the brewery showed that in addition to all the process streams being below 104 °C, it was found that about 80 % and 40 % of the heating utility is required below 80 °C, and 60 °C respectively. Furthermore, almost the entire cooling utility is required below 35 °C. The Temperature level required for heating questions using steam as heating media, and showed a potential for utilizing a hot water system instead. Replacing the central steam boilers with central hot water boilers would lead to energy savings since hot water boilers have better efficiencies.

In general, it was seen that the processes in the brew house were responsible for 57% of the total hot utility demand at the brewery. The largest consumers of hot utility in the system are the wort production in the brew house, the CIP processes and the brew house boiler. In total, the actual utility usage at the brewery was found to be 3915 kW of heating utility and 1213 kW of cooling utility.

Form tradition pinch analysis, the pinch point of the system can be identified as 12.5 °C. This therefore leads to a total energy-saving potential in the system of 1288 kW, equal to 25.1% of the total utility usage.

The 1st simplification step of ESD method s reduced the system size from 49 to 12 streams, equal to a 76 % reduction, while keeping the 91 % of the original energy-saving potential in the remaining system. The 2nd simplification of the ESD method it was concluded that the only pinch violation that could be solved feasibly was caused by the wastewater stream. Finally, A Heat exchanger network that incorporates the wastewater stream at Harboe into the system by preheating raw water for the wort production and uses raw water instead of ice water for cooling wort after the whirlpool was proposed. This HEN achieved 434 kW hot utility savings and 446 kW cold utility savings with 2.7 years PBT, considering heat exchanger, piping and buffer tank costs.

Electrification of Harboe

Figure 3 shows the annual energy consumption in terms of natural gas and electricity for all the scenarios.

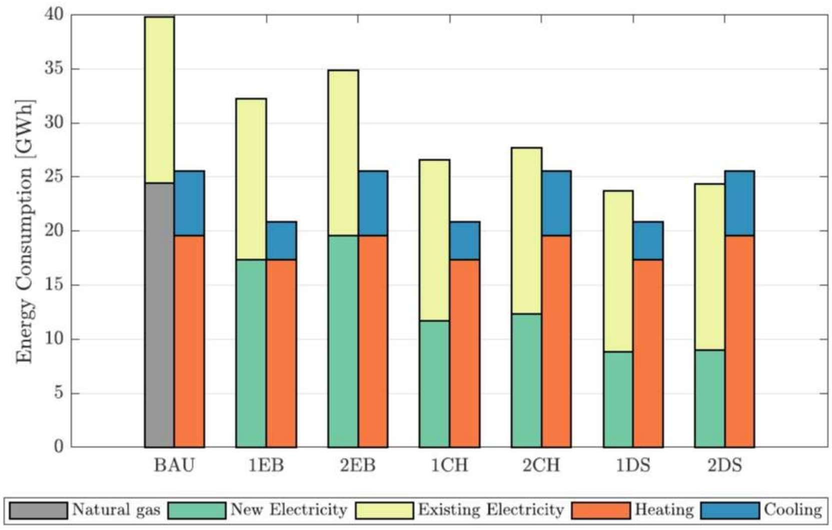

Figure-3: Total energy use of the scenarios in the screening phase, 1 and 2 represents the scenarios with and without hear recovery respectively

For the electric boiler scenarios (1EB and 2EB) it can be seen that the electricity consumption matches the heating demand completely due to the assumed efficiency of 100 %. Therefore, the overall energy-savings are not very significant compared to the BAU scenario. By replacing the boilers with heat pump systems, the energy consumption can be significantly reduced. In addition, it was shown that the scenarios including the internal heat integration obtained lower energy consumption and higher annual savings. Nevertheless, the effect was smaller in the heat pump scenario due to impact on the coefficients of performance (COP) of the individual heat pumps.

The three selected scenarios, scenario A, B and C, could achieve a total energy consumption of about 7.53 GWh, 13.21 GWh and 15.44 GWh with COP_h values of 1.12, 1.67 and 2.17 respectively. Comparing case B with Case C shows that Case C (decentral system) saves more energy and significantly improves the overall COP_h of the system. The drawback is that the system requires significantly more components in order to be implemented.

The economic analysis showed that the electric boiler scenario was infeasible under current energy prices with a negative NPV of 11.96 MDKK. The central heat pump and decentral system both had positive NPV values of 7.99 MDKK and 19.01 MDKK with a discount pay back time of 13.7 years and 9.4 years respectively. An investigation further showed a potential for reducing the payback time of the decentral scenario to 6.0 years by investing in 2030.

The environmental analysis showed that for 2020, the scenarios were able to cut CO2 emissions in half and by 2050, with an increased renewable penetration in the grid, the CO2 emissions could be reduced by up to 87%.

General approach for electrification of low-to-medium temperature production industries

Based on the knowledge and experience gained throughout the project, a set of recommendations and guidelines for carrying out general electrification studies have been created.

A process scheme of the suggested electrification strategy is presented in Figure 6.3. The overall strategy consists of two phases: a pre-screening phase and an analysis phase. During the pre-screening phase the existing system is thoroughly studied, to ensure a good understanding of the system at hand. The goal of this phase is to produce a set of scenarios that can be carried over to the analysis phase. A set of research focuses for the scenarios are also defined in the process scheme. These are based on the experience gained throughout the project and should only be considered as suggestions. In the analysis phase, the created scenarios are first screened, leading to a selection of best cases. The selected scenarios are then evaluated based on their thermodynamic and economic performance.

In total, the strategy consists of 8 steps. Each step will be further explained in the following:

1. In the first step of the analysis a detailed energy mapping of the system should be carried out. This lays the foundation for the entire analysis, and is therefore a key part of the electrification strategy. Focus should be on understanding all the individual processes in the system, to allow electrification measures to be implemented on a process level.

2. In the second step a process integration analysis is carried out. In this step, the internal heat recovery potentials are investigated and a HEN can be proposed. In this step the traditional pinch method can be applied, and potentially be combined with the ESD method to save time, as was the case in this thesis. During this step, the analyst will get a better overview of the available heat sources, which could be utilized for e.g. heat pump integration.

3. In step 3, a literature review of alternative technologies should be conducted. This is very important, since a lot of electrification technologies are still under development, so changes can happen rapidly. It is advised to study both process level and utility level integration technologies.

4. Step 4 is the conclusion of the pre-screening phase, where the output should be a set of distinctive electrification scenarios. As it was discussed in Section 6.2.3, a lot of technologies are available to the analyst which is why the strategy includes suggestions to areas that should be covered by the scenarios. Having scenarios in all areas enables the analysis phase to answer two important questions:

a) Does the HEN from the process integration benefit the electrification analysis? Or is it competing with technologies e.g. heat pumps?

b) Should electrification be integrated on a process level or a utility level?

These were some of the key questions found during the work of this thesis.

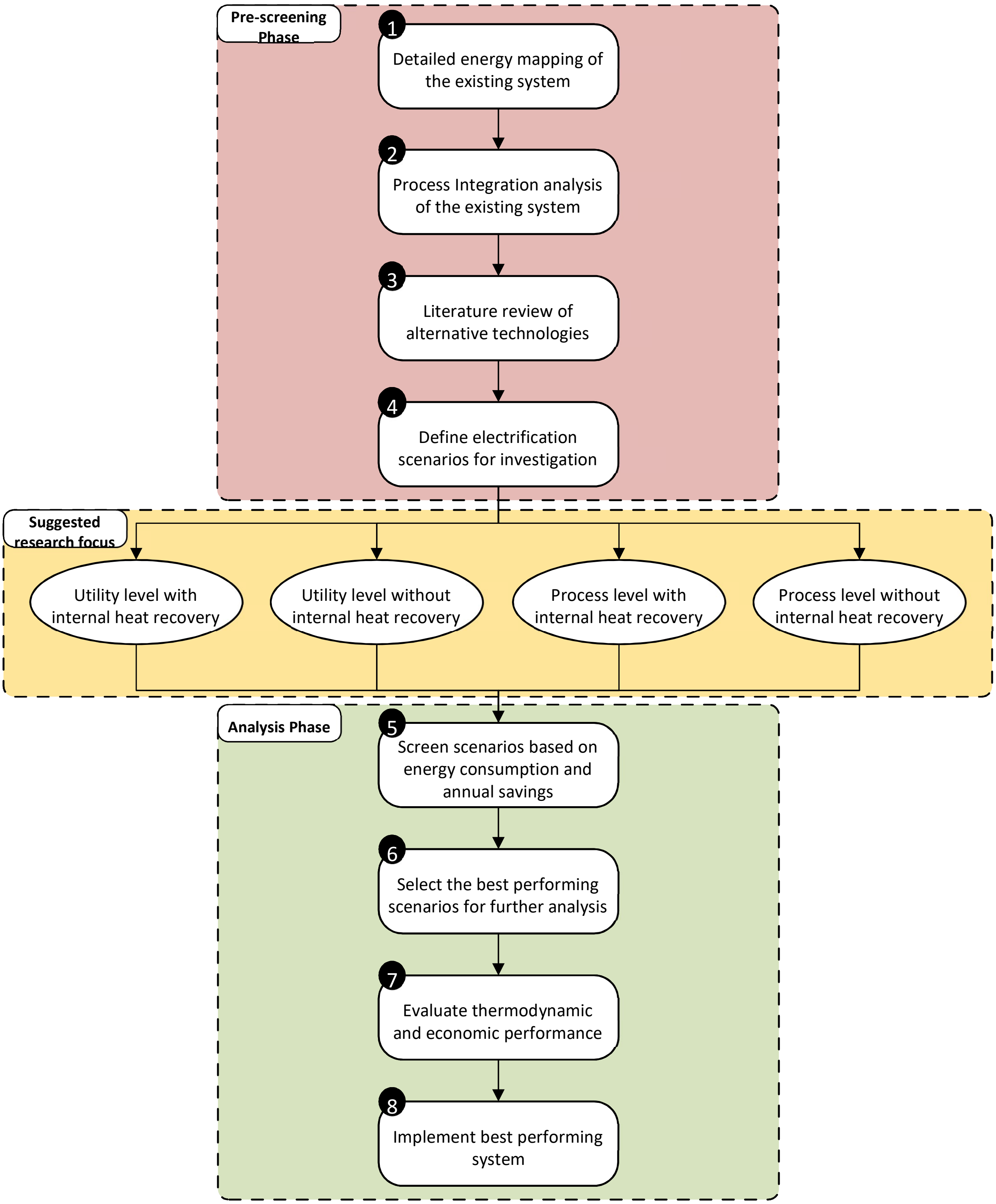

Figure-4 Process scheme of the suggested general electrification Strategy

5. Step 5 is the first step of the analysis phase. Here, all the created electrification scenarios are screened against each other. It is suggested to do this in terms of the energy consumption and annual savings. If heat pumps are included in the scenarios, it is suggested to use a Lorentz efficiency approach for estimating the energy consumption of the scenarios. This can help the analyst save time while being sufficiently accurate to carry out the screening.

6. In step 6, the best performing scenarios from the screening are selected and carried over to the further analyses.

7. In step 7, the remaining scenarios are analyzed in terms of thermodynamic and economic performance. The analyses can have various level of detail in terms of modeling, depending on the desired outcome of the analysis. For this study, the simple Lorenz efficiency was kept for this part of the analysis, but a more detailed modeling approach would give the analysts a more conclusive result. However, it is important to keep in mind not to underestimate the potentials of the electrification strategies.

8. Step 8, is the final step of the electrification strategy. Based on the economic and thermodynamic evaluations, the best performing electrification scenario can be selected for implementation.

By carrying out the proposed eight steps, a large amount of initial electrification scenarios can be boiled down to a single electrification strategy to be implemented. The benefit of the screening phase is that a large number of scenarios with many different combinations of technologies can be easily evaluated without extensive thermodynamic models. The most promising scenarios can then be modeled to the desired level of the analyst.

Conclusion

The present study investigates the potentials for energy optimization and electrification for the specific case of a Harboe brewery. This case presented a good potential for electrification due to all the process heat demands being below 104 °C. It is believed that the findings and utilized methods can be applied to other industries with low-to-medium temperature process heat demands, thereby furthering the ongoing research in electrifying Danish industry.

For the Harboe case study, the results showed that the best solution would be a decentral system utilizing a heat pump source loop with the best economic performance (NPV equals to 19.01 with DPBT' of 9.4 yeard) out of the investigated scenarios. The analysis showed that the model was most sensitive to changes in natural gas and electricity prices. More work should therefore be put into estimating the uncertainty in regards to these prices.

Acknowledgment

This research project was financially funded by Elforsk, the research and development fund of the Danish Energy Association, under the project (350-038) "Electrification of process and technologies in the Danish industry". The authors thanks the institutions, which shared relevant data and industry knowledge: SAN Electro Heat A/S.

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Welcome

Energy Optimization and Electrification Study of a Brewery

MSc Project, Andreas Helk

Viegand Maagøe

Agenda

1. Introduction
2. Background
3. Methods
4. Results
   - Process Integration
   - Electrification Analysis
5. Discussion
6. Conclusion

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1. Introduction

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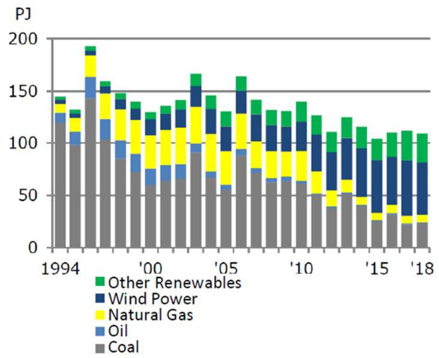
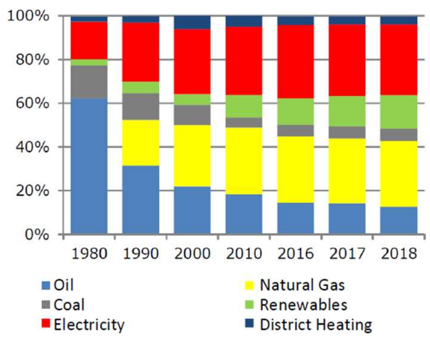
Motivation

Industry has an important role in meeting the goals of the Paris Agreement.

1. Natural gas still accounts for 30% of total energy consumption in manufacturing industries.
2. 69% of electricity production from renewables





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Goals and Tasks

Overall goal: Investigate potentials for energy optimization and electrification strategies for the Harboe brewery.
Thereby contributing to the ongoing research in electrifying Danish Industry.

Tasks:

- Energy System Mapping
- Process Integration Analysis
- Electrification Analysis
  - Screening a Set of Electrification Scenarios
  - Economic Feasibility Study
  - Environmental Evaluation
- Presentation of a General Electrification Strategy

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2. Background

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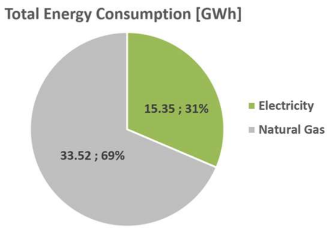
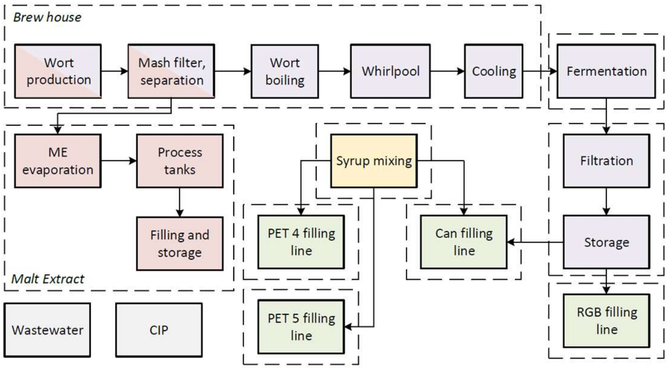
The Harboe Brewery

- Main products from the brewery are beer, malt extract products and soft drinks.
- Energy consumption consists of natural gas and electricity.





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3. Methods

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Overall Method

- Energy systems mapping
- Process integration analysis
- Electrification analysis
  - Screening based on energy consumption and annual savings in the first year of operation

	1EB	2EB	1CH	2CH	1DS	2DS
Central Electric Boiler	X	X				
Centralized HP			X	X		
Decentral HP's and Electric Heaters					X	X
Internal Heat Recovery	X		X		X	

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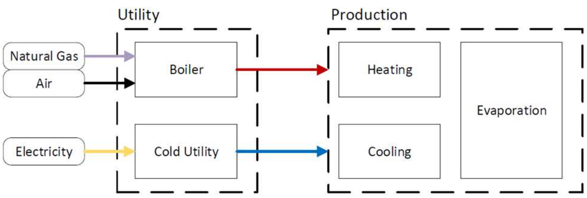
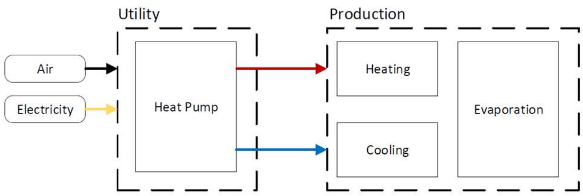
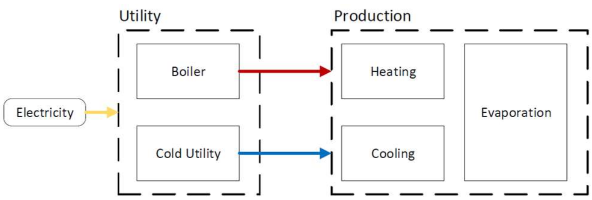
Structure of Scenarios



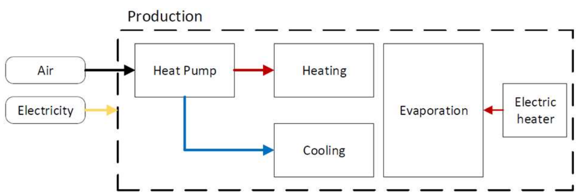
(a) BAU scenario with central natural gas boiler and cooling unit.



(c) CH scenario with central heat pump system.



(b) EB scenario with central electric boiler and cooling unit.



(d) DS scenario with decentral heat pumps and electric heaters.

4. Results

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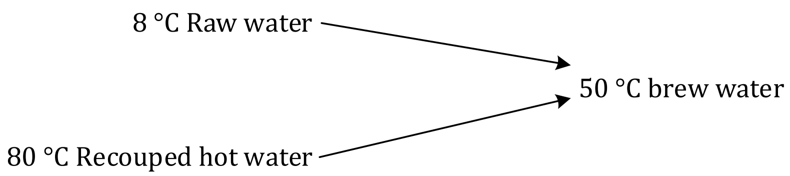
Process Integration Analysis

A Heat Exchanger Network was designed, using wastewater to preheat water for the wort production.

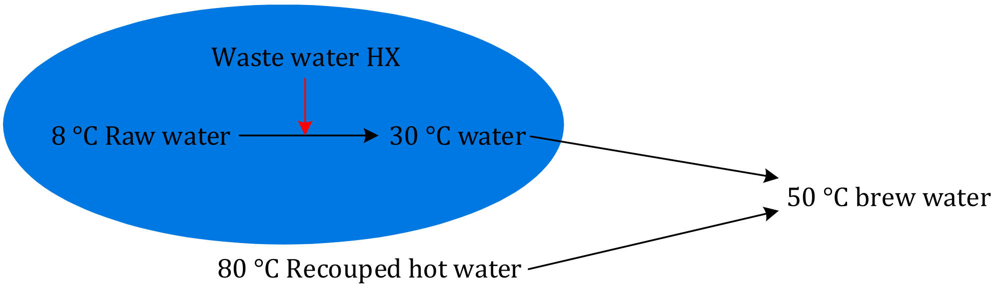
Before:



Process Integration Analysis

A Heat Exchanger Network was designed, using wastewater to preheat water for the wort production.

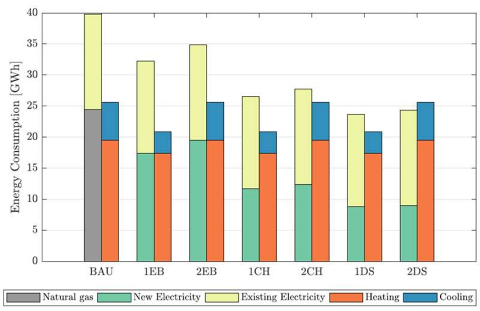
After:

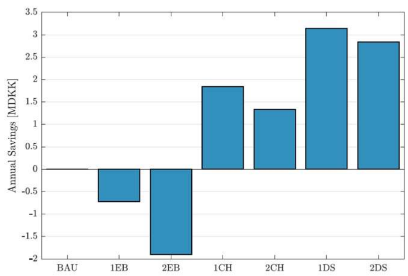


1.69 GWh annual energy savings with PBT of 2.7 years

Electrification Analysis

Scenario screening





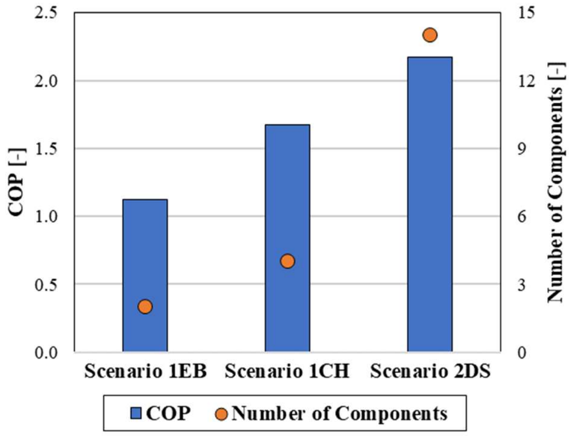
Scenario	Description	Reduced energy consumption [GWh]	Annual Savings [MDKK]
1EB	Electric Boiler with heat integration	7.53 GWh (19%)	-0.72
1CH	Centralized HP with heat integration	13.21 GWh (33%)	1.84
2DS	Decentral System without heat integration	15.44 GWh (39%)	2.84

Electrification

Energy analysis

Trade-off between thermodynamic performance and number of components.

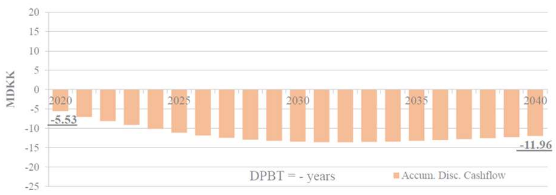
- Heat pumps in decentral system have significantly smaller temperature lifts



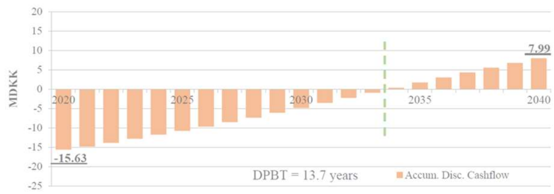
Electrification

Feasibility study

(c) Scenario 2DS



(a) Scenario 1EB



(b) Scenario 1CH

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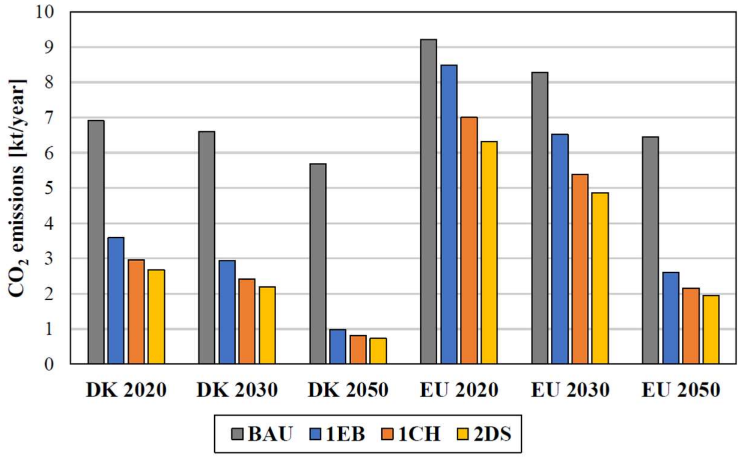
Environmental Evaluation



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5. Discussion

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Electrification strategy for Harboe

- The overall recommendation is to implement a decentral heat pump system without the developed HEN.
- Scenario yields an NPV of 19.01 MDKK and a PBT of 9.4 years.
- System COP of 2.17 and 15.44 GWh of energy savings.
- Benefits:
  - The scenario can be implemented in stages
  - Easier to exchange broken components
- Draw-backs:
  - Large layout changes (utility level to process level)
  - Could require more personnel

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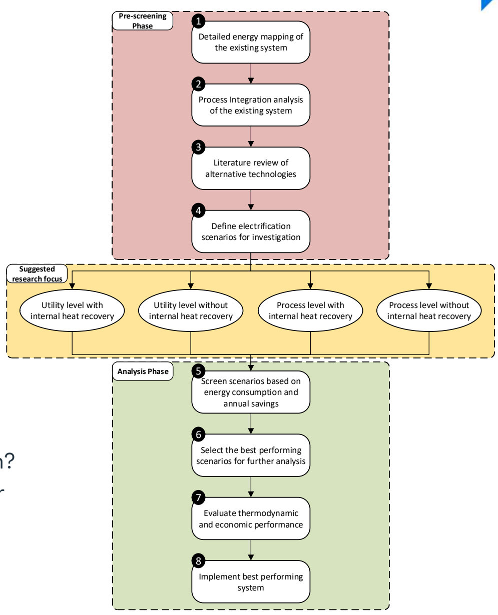
General Electrification Strategy

Strategy consists of two phases

1. Pre-screening phase:
   - Thorough study of existing system
   - Output is a set of electrification scenarios
2. Analysis phase:
   - Thermodynamic, economic and environmental performance is evaluated
   - Leads to a selection of the best performing scenario
   - During the screening it is suggested to focus on two primary questions:

     Does the HEN from the PI benefit the electrification?

     Should electrification be integrated on a process or utility level?



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6. Conclusion

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Final Remarks

- Potentials for energy optimization and electrification at the Harboe brewery were investigated.
- **Electrification Analysis**: Thermodynamic, economic and environmental performance was investigated.
  - **Final Recommendation**: A decentral heat pump system without process integration measures.
  - System COP of 2.17 and 15.44 GWh of energy savings
- A general electrification strategy was proposed
  - Screening based approach
  - Process integration or not
  - Central vs. Decentral

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Thank you for listening!

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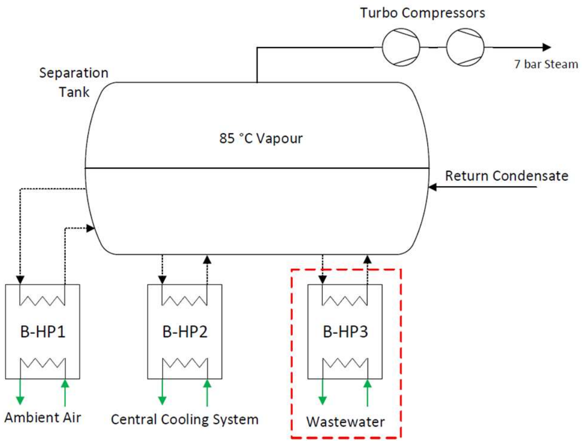
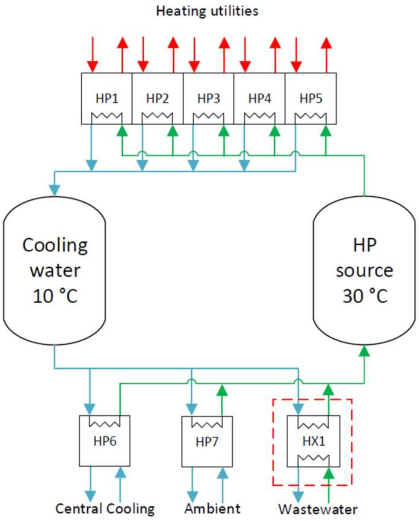
7. Appendix

Additional slides for break-out room

Modeling approach

- All heat pumps modeled with a Lorentz COP approach





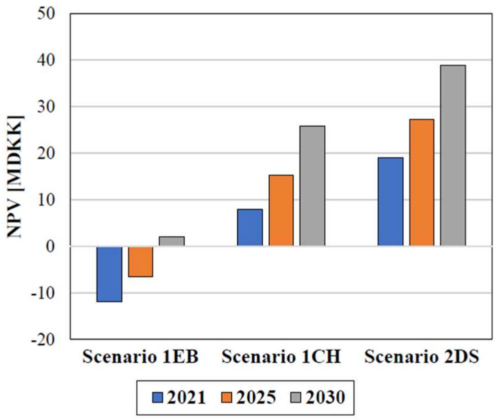
Process Integration

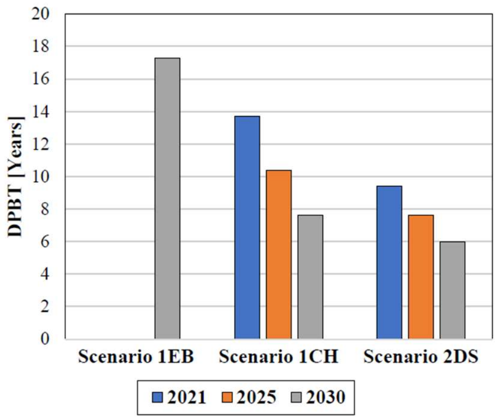
Economic evaluation

Parameter	Value	Unit
Heat exchanger size	339	kW
Cost of Heat Exchanger	0.87	MDKK
Cost of Piping	0.69	MDKK
Cost of Tank	0.83	MDKK
Total Cost of Investment	3.25	MDKK
Subsidy	0.88	MDKK
Revenue	0.86	MDKK/Year
Payback Time	**2.7**	**Years**

Electrification

Investment year





Energy Prices

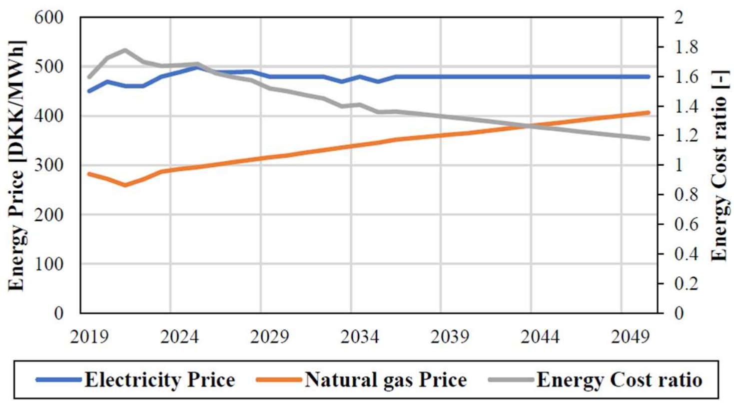


Figure 4.7: Projection the natural gas- and electricity prices and the ratio between the prices.

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Emission Factors

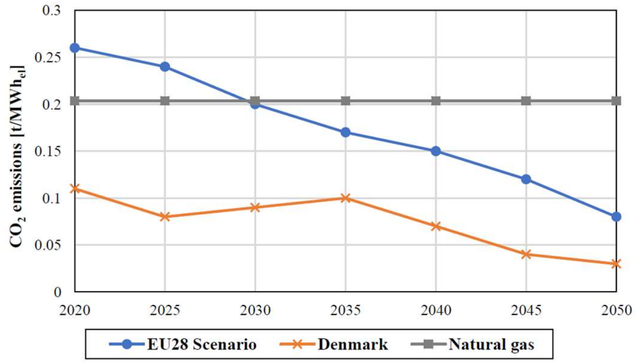

Figure 4.8: CO_2 emission factors of natural gas and the electricity mix of Denmark and the EU-28 reference scenario.

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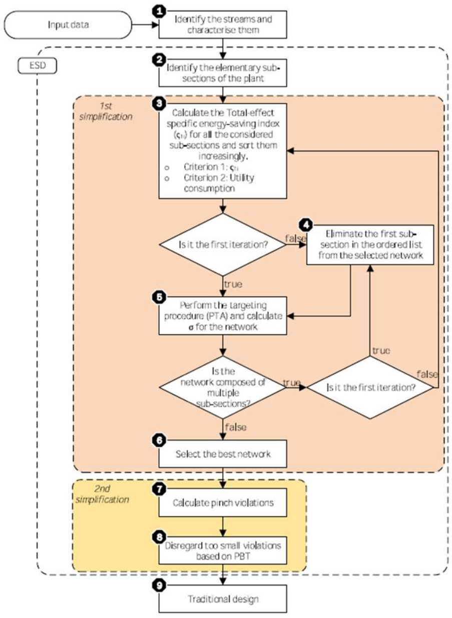
Process Integration

ESD 1st simplification



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MEMO

Project:	**1775 – ELFORSK – Electrification**
Subject:	**Electrification of CP Kelco steam supply**
Date:	**2020.02.12**
To:	**ELFORSK**
Copy to:	**CP Kelco A/S**
From:	**Andreas Helk (Viegand Maagøe A/S), Emil Lundager Godiksen (SAN Electro Heat A/S), Fridolin Müller Holm (Viegand Maagøe A/S), Vegard Hetting (CP Kelco ApS), Esben Jacobsen (CP Kelco ApS)**

1 Introduction

The following case study aims at examining the technical and economic feasibility of electrifying the entire steam supply of a production facility via a central or partly decentral electric heating system. The case study considers the chemical plant of CP Kelco ApS (hereafter CP Kelco), which is located in Lille Skensved, Denmark. CP Kelco is a leading global producer of nature-based ingredients which are used to improve texture and stability in food products and pharmaceutical and personal care applications. CP Kelco ingredients are also used in various household care products and industrial applications. The plant in Lille Skensved is one of the largest of its kind in the world and produces pectin and carrageenan based on citrus peel and seaweed, respectively. In addition to these, the facility also produces Locust Bean Gum (LBG) from Locust bean seeds.

CP Kelco is in the process of electrifying their entire utility system. This will not happen overnight but is going to be a stepwise process over a 10-year period. Therefore, a masterplan of the entire process has been created. The first two stages of the electrification are:

1. Electrifying low temperature processes with heat pumps
2. Electrifying evaporation processes and distillation columns with Mechanical Vapor Recompression (MVR).

The third and final stage is to electrify the remaining high temperature processes that all require a supply of steam. In the masterplan, this is projected to be implemented in the year 2031. The following case study therefore examines the feasibility of using electric heaters to supply the remaining heat demands. The analysis is based on implementing currently existing technologies. The study is carried out in cooperation with SAN Electro Heat who specialize in delivering electrical heating solutions to industry [1]. They have therefore provided expert knowledge in the system designs and have provided real costs for the components that have been analysed.

The memo first briefly describes the system at CP Kelco, focusing on the overall remaining system and the developed solutions. Next, the economic considerations are described, and the total energy usage is analysed. All this feeds into the economic analysis of the solutions. Finally, the results are discussed, leading to a conclusion of the study.

2 System Description

As mentioned, the CP Kelco plant is going through a big transformation in the upcoming years. This project only considers the remaining steam demand in stage 3 of the masterplan. Figure 1 gives an overview of the projected steam consumption at the plant in GWh from 2020 to 2033. It is seen that the leftover steam consumption in 2031 is equal to 31,1 GWh of steam annually. This energy is used for extraction and drying processes which require either high temperatures or steam injection. Around 59% of the remaining energy demand is currently supplied by means of steam injection. Today, the entire steam demand is produced on 4 central boilers mainly utilizing natural gas. The plant also uses about 9,1 GWh of biogas annually which will also be available in the year 2031. However, since this supply can be rather unreliable, the designed electric boiler systems are still required to have enough capacity to cover the entire plant.

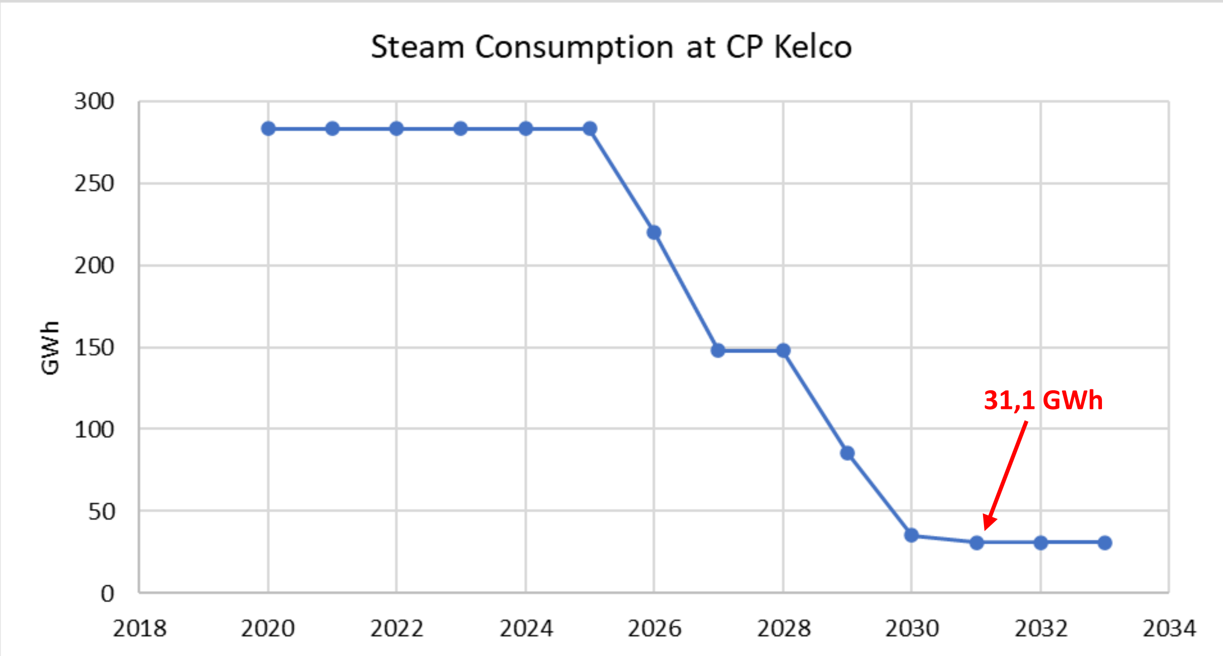

Figure 1: Projected steam consumption at the CP Kelco facility.

Based on the energy demands of the various remaining processes two different scenarios were examined. One system consisting of a large central electric boiler and one system consisting of a smaller central electric boiler and local immersion heaters. A simple schematic of the two systems is shown in Figure 2. The two systems are described in more detail in the following sections.

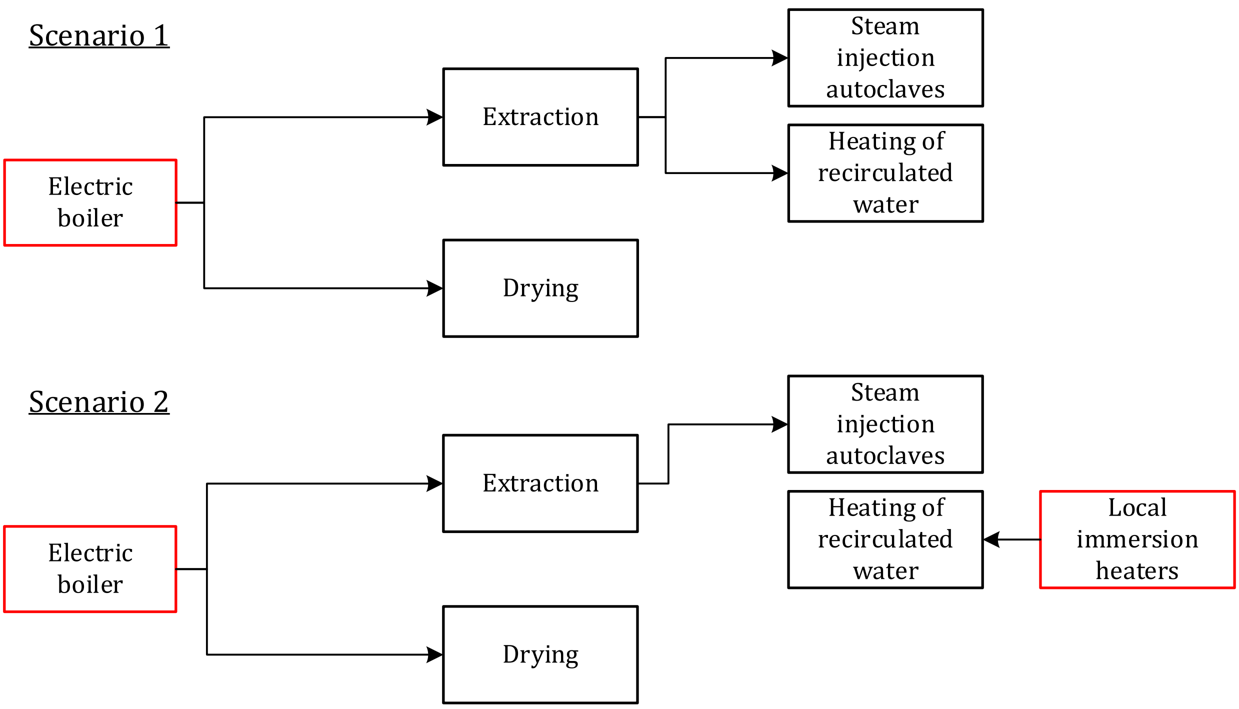

Figure 2: Schematic representation of the two scenarios

2.1 Large Central Electric Boiler

The first system that has been examined is very simple. It consists of switching out the existing central natural gas boilers with a central electric boiler. Thereby the steam distribution system is kept the same. This electric boiler should therefore be able to provide the entire steam demand. Once again assuming 8000 annual operation hours, the system would require 3,89 MW of boiler capacity. In the analysis, a 4 MW electric steam boiler has been considered, providing some excess capacity for peak loads. In Appendix B a simple illustration of the implemented type of electric boiler is shown.

2.2 Local Immersion Heaters and Smaller Central Electric Boiler

In the second scenario part of the heat is supplied locally while the rest is supplied by a smaller central electric boiler. The local heat demand that is being supplied for reheating recirculated water from the extraction process. Currently, this is done via steam injection, but in this scenario immersion heaters are inserted into the tanks. The heaters can then increase the temperature from 65°C to the required 85°C and keep the temperature at 85°C until it is needed for a new batch. A schematic of a standard immersion heater is shown in Appendix A. The CP Kelco facility has 4 of these recirculation tanks, meaning that 4 immersion heaters are required. The capacity of each immersion heater unit varies between 400 and 600 kW. In total, the immersion heaters provide about 46% of the total heat demand in the second scenario. Additionally, a 2 MW central electric boiler is installed, to cover the remaining demand for steam.

3 Economic Considerations

To compare the projects to one another, the total costs over the first 10 years of operation from 2031 to 2040 were analysed for the two scenarios. Additionally, the two scenarios were compared to a base case where the original central natural gas boiler is kept. The most important cost factor in the analysis then becomes the fuel cost since this is an annual payment for operating the systems. Since the project is expected to be installed in the year 2030, a forecasted electricity price from the Danish Energy Agency has been utilized for the analysis [2]. This forecast expects the electricity price in 2030 to have reached a stable level. To reflect the actual cost of electricity at the CP Kelco facility, transmission and distribution fees are added as well as a small fee for electricity usage for processes. The electricity price has therefore been assumed as 555 dkk/MWh over the entire 10-year period for both cases.

When analysing the base case, a constant natural gas price of 279 dkk/MWh has been used. This price is based on forecasted raw prices of natural gas from the Danish Energy Agency, but adding fees for transmission and distribution, process usage and CO_2 emissions [2], [3]. For the base case CO_2 quota prices have also been considered based on projections of the Danish Energy Agency [2].

Investment costs of the electric heating scenarios were found by obtaining offers from SAN Electro Heat for the components. The investment costs are summarized in Table 1. The costs also account for purchasing breaker panels and all relevant armatures and valves for connecting the boilers. As expected, the second scenario requires higher investment costs due to having more components. However, since the immersion heaters have a lower cost per MW, the cost is only slightly higher. As it was stated previously, the analysis considers 10 years of operation. The investment cost of the projects only make up 7-8% of the annual cost of electricity for the systems, so over the 10 year lifetime, the impact of the investment cost will be miniscule.

Table 1: Investment costs of the two scenarios.

	Components	**Investment cost [dkk]**
Scenario 1	1 x 4 MW electric boiler	1.318.200
Scenario 2	1 x 2 MW electric boiler 4 x immersion heaters	1.472.390

4 Energy Analysis

Before carrying out the economic analysis of the projects, an energy analysis was made to further the understanding of the scenarios. Figure 3 shows the total energy consumption of the three solutions. All three cases have the same process heat demand. However, it is seen that the energy losses are significantly larger in the base case due to the lower efficiency of the boiler. When exchanging the natural gas boiler with an electric boiler only the distribution losses remain, and the overall energy usage decreases by 8%. Finally, when providing part of the heating locally in scenario 2, the losses are further decreased due to only requiring approximately half the amount of steam. This means that the overall energy usage is decreased by 12,5% compared to the base case.

It should be noted that in the following analysis the new central electric boilers were assumed to be placed at the same location as the original natural gas boiler, and therefore having the same amount of distribution losses. This was chosen because of the limited knowledge about the space limitations around the CP Kelco facility. However, the distribution losses could be further decreased by placing the new boilers closer to the processes if possible.

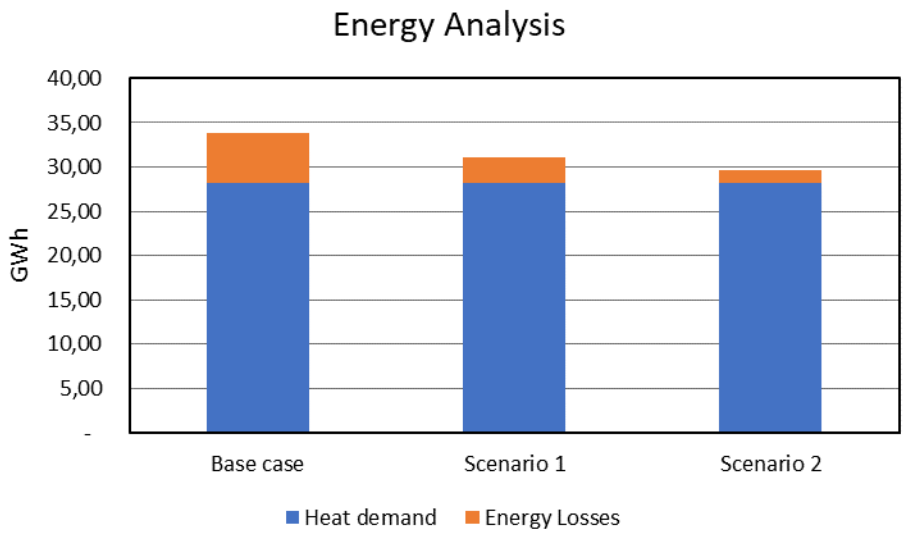

Figure 3: Energy analysis of the scenarios.

5 Economic analysis

Next, an economic analysis was carried out. As described earlier, this was carried out by comparing the total cost over 10 years of operation. In Figure 4 it is seen that the cheapest solution would be to keep using a central natural gas boiler due to the lower fuel cost. The energy savings from electrifying are therefore not enough to outweigh the fuel costs. However, with the goal of achieving 100% electrification, it is seen that scenario 2 outperforms scenario 1 by about 5%. The energy savings that are achieved from providing part of the heat locally, are therefore directly reflected in the total cost of the projects.

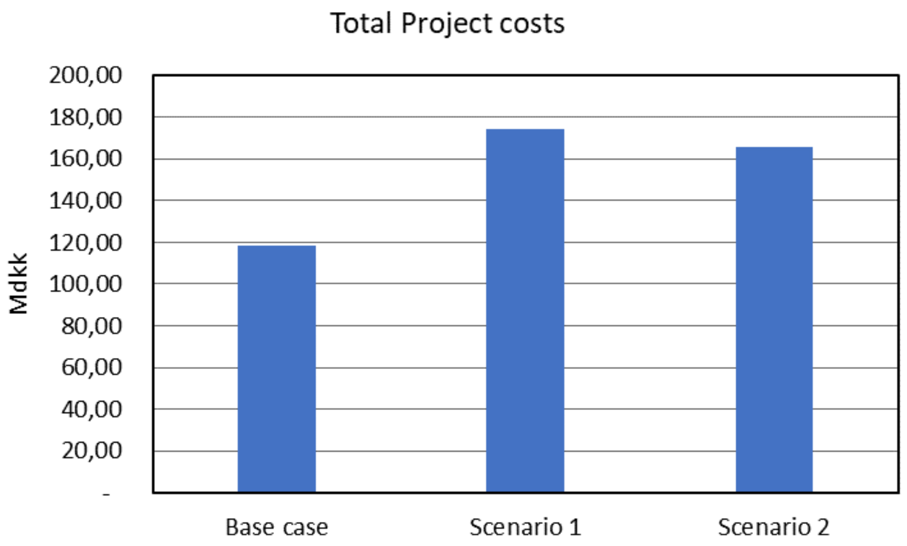

Figure 4: Total project costs over 10 years of operation.

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6 Discussion

The project has analyzed how to electrify the final 11% of the CP Kelco facility. These heat demands are therefore also the most difficult ones to provide economically feasible electrification solutions for. Due to the high temperatures and demand for steam, no electrification technologies currently exist that can provide a high enough COP to make up for the relationship between electricity and natural gas prices. To reach 100% electrification of a site one should therefore look at the project as a whole, since many lower temperature demands and evaporation processes can be electrified at a COP much higher than 1 through heat pumps and MVR technologies. Figure 4 shows that electrifying the final 11% of the energy demand will require 41% higher costs compared to the base case of not changing anything. Using the same electricity and natural gas prices for 2030 as stated previously, the remaining system would require a system COP of 2,0 to recover the additional investment of the electric boilers in 10 years. In the current masterplan, the system COP of the 89% of the heat demand is projected to be 5,44 (mainly driven by the very high COP of MVR). This can therefore easily cover the increased cost of electrifying the final 11% of the energy demand. This is an important issue to consider in regard to achieving the CO_2 reduction goals for 2030 set up by the Danish government. To achieve this, industry will have to start developing full strategies on reducing emissions. The strategy should always focus on implementing the best economical cases first, but if the goal is 100% electrification most industries should consider that the final percentages will also be the most expensive, so considering them in a larger context is important.

7 Conclusion

CP Kelco is currently exploring possibilities of reaching 100% electrification of their entire facility. The first 89% of the heat demand can be achieved via existing heat pump and MVR technologies. However, the remaining 11% can require high temperatures and can therefore not be covered by these existing technologies. This led to the creation of two scenarios exploring a central electric boiler and a combination of local immersion heaters and a smaller central electric boiler. The investment costs of these systems are miniscule compared to the annual electricity costs, making the energy usage the driving factor of the analysis. The study has shown that providing part of the heat locally provides about 4,5% total energy savings.

Due to the relation between natural gas and electricity prices, both of the projects are economically infeasible compared to just continuing with natural gas. However, when looking at the electrification project as a whole, the first two phases of the master plan are sufficiently efficient, to still achieve a positive business case in the end.

8 References

[1] SAN Electro Heat, “Industrial Electrical Heating Solutions,” [Online]. Available: https://www.san-as.com/business-areas/industrial.html. [Accessed 24 Nov 2020].

[2] Danish Energy Agency, “Basisfremskrivning 2020,” Danish Energy Agency, 2020.

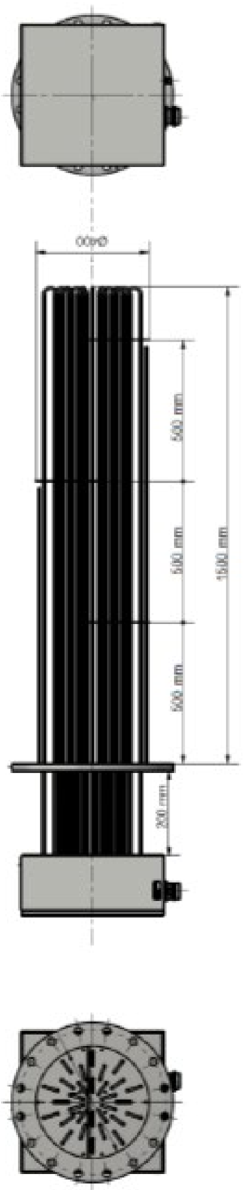
[3] Skatteministeriet, *Forhøjelse af energiafgiften for erhverv,* Skatteministeriet, 2020.

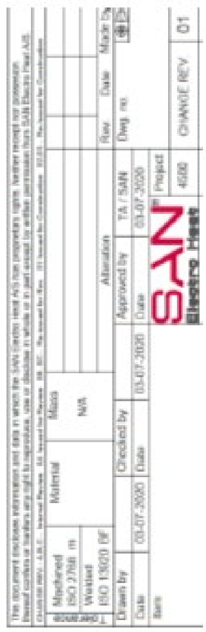
9 Appendices

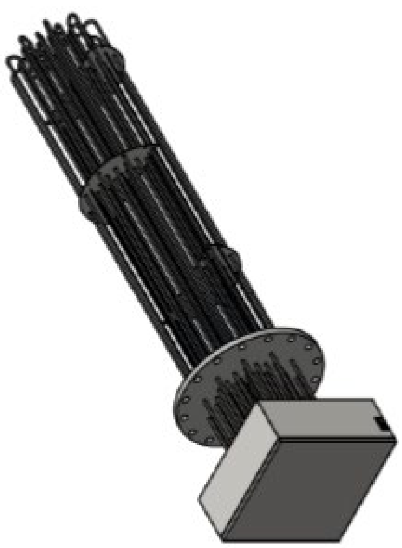
A. Immersion Heater

SAN® Electro Heat

Member of the NIBE Group







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B. Central Electric Boiler

Illustration of the implemented Danstoker electric boiler.

Viegand Maagøe

Welcome

Electrification of CP Kelco Steam Supply

Viegand Maagøe

Agenda

1. Introduction
2. The CP Kelco Case
3. Scenario Descriptions
4. Energy Analysis
5. Economic Analysis
6. Discussion
7. Additional Solutions (SAN Electro Heat)

1. Introduction

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The Project

- **Motivation:** Study the possibilities of electrifying high temperature processes
  - Currently heat pumps can only take you part of the way
  - Reaching 100% electrification will therefore require additional technologies for most companies
- Analysis is carried out by:
  - **Viegand Maagøe** – consultancy
  - **SAN Electro Heat** – Supplier of electric heating solutions for industries
- Case study of CP Kelco facility

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2. The CP Kelco Case

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CP Kelco Description

- Located in Lille Skensved, Denmark
- Leading producer of nature-based ingredients for food products and pharmaceutical and personal care
    - Produces pectin and carrageenan based on citrus peel and seaweed, respectively
- One of the largest of its kind in the world

CPKelco Unlocking Nature-Powered Success
A HUBER COMPANY

Viegand Maagøe

The CP Kelco Masterplan

- 100% electrification of the facility
- Three stages over a 10-year period
  1. Electrifying low temperature processes with heat pumps
  2. Electrifying evaporation processes and distillation columns with MVR
  3. Electrifying high temperature processes
- Step 3 is the focus of this project

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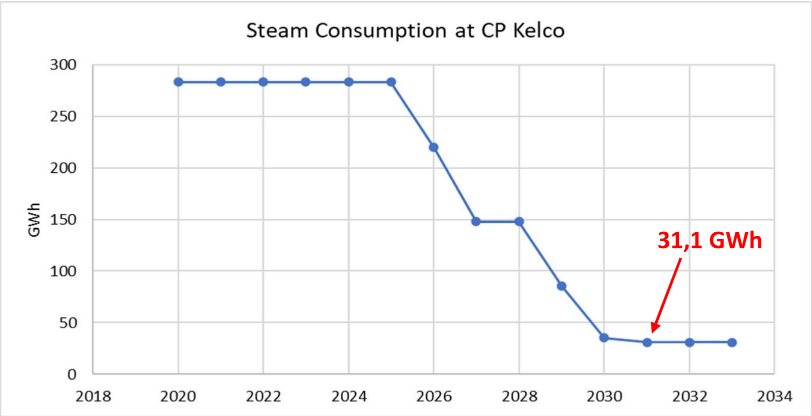
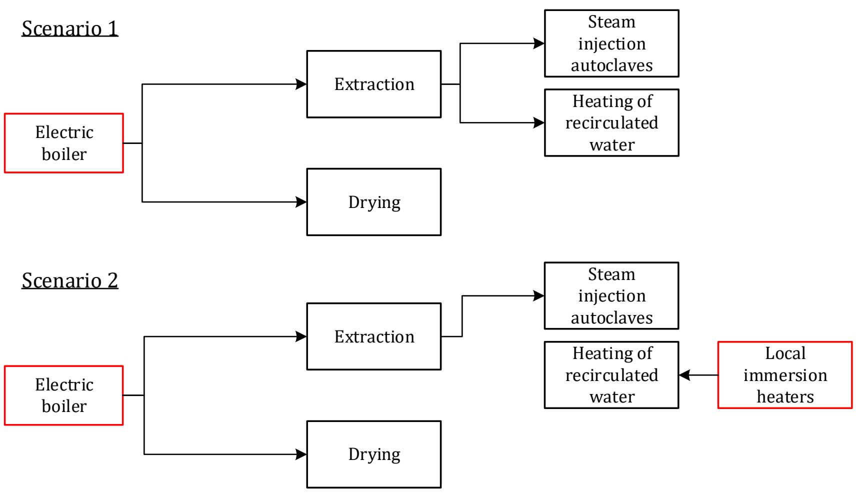
Projected Steam consumption

- Steam consumption is projected to decrease by 89% from 2020-2031
- Remaining consumption is from drying and extraction processes
- 59% of remaining steam consumption done by direct steam injection



3. Scenario Descriptions

General Overview



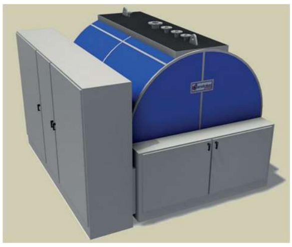
Scenario 1

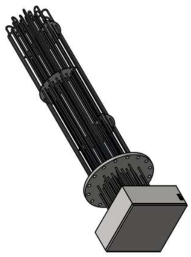
Central Electric Boiler

- Central natural gas boiler exchanged 1:1 with electric boiler
- Implementation of a 4 MW central electric boiler from Danstoker
- Investment cost of **1.318.200 dkk**
  - Including breaker panels, armatures and valves
- Same distribution losses as the original natural gas system

Scenario 2

Central Electric Boiler and local immersion heater batteries





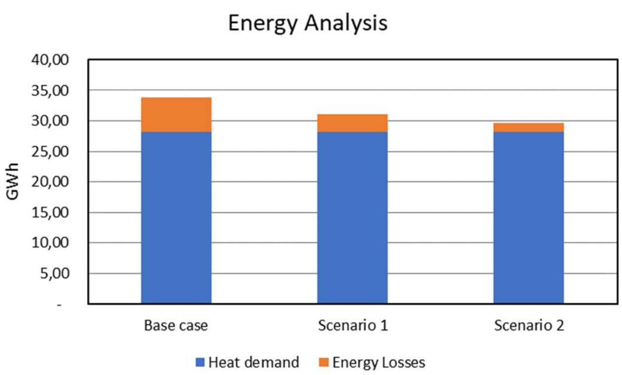
- Central natural gas boiler is exchanged with a smaller 2 MW central electric boiler
- 46 % of the remaining energy demand supplied by local immersion heater batteries
  - Reheating of recirculated water for extraction process
  - Currently using direct steam injection
  - 4 batteries with capacities between 400-600 kW
- Investment cost of **1.472.390 dkk**

4. Energy Analysis

Viegand Maagøe

Analysis of Total Energy Consumption

- **Scenario 1**: Energy consumption decreases by 8%
  - Distribution losses remain the same
- **Scenario 2:** Energy consumption decreases by 12,5%
  - Reduced distribution losses due to requiring half the amount of steam
- **Note**: Potential for further reducing distribution losses by placing new boilers closer to the processes



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5. Economic Analysis

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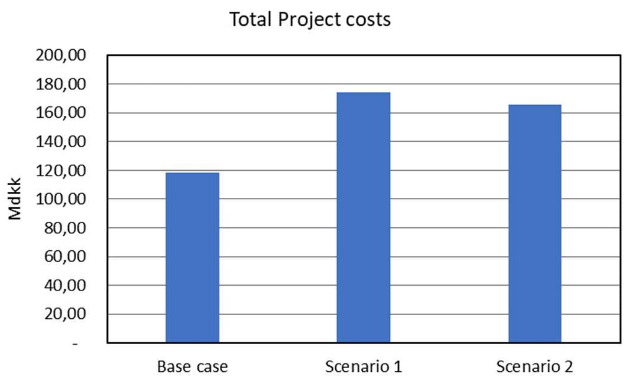
Analysis of the Total Project Costs

- Comparing total project cost over 10 years of operation
- Cost-wise continuing with natural gas is preferable
    - Relation between natural gas and electricity prices
- Scenario 2 outperforms scenario 1 by 5% due to the additional energy savings



6. Discussion

Discussion

- Electrifying the final energy demands pose the greatest challenge
  - Economically challenging due to relation between natural gas and electricity prices
  - Requires technologies with higher COP
- To reach 100% electrification one could consider the entire electrification project as a whole
- At CP Kelco:
  - Scenario 2 has 41% higher costs than Base case -> The remaining 89% requires system COP of 2.0 to make up for this
  - In current Masterplan the first 89% electrification has a system COP of 5,44
  - The project as a whole still gives a positive case

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7. Additional Solutions

Electric heating solutions for industrial high temperature processes

SAN Electro Heat

SAN PROCESS HEATING

Tubular heating technology

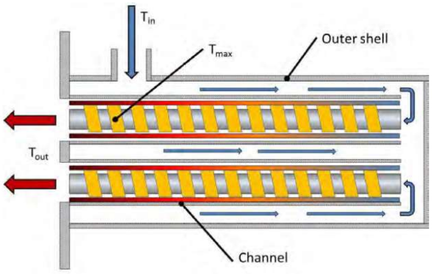
- Traditional resistance heating element for high power high flow solutions.
- Used for gas heating in the 5kW to +10 MW, max 650°C

SAN PROCESS HEATING

Closed Coil heating technology

- High temperature gradient solution for low gas flows.
- Designed for compact heating of low flow systems

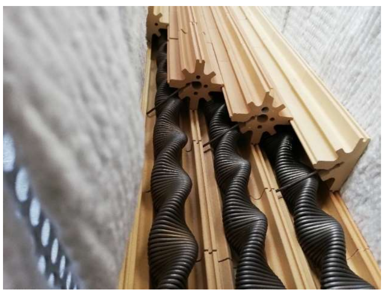
  with high temperature gradients.

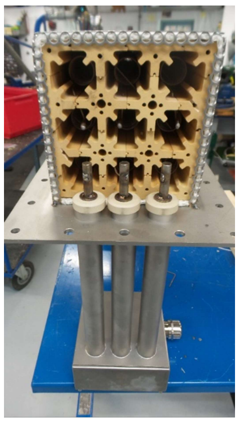


SAN PROCESS HEATING

Open Coil heating technology

- High temperature solution up to 850°C.
- Designed for oil/gas replacement.
- Currently up to 75 kW
- Aiming for +1000°C and 250 kW.





SAN Electro Heat

VISION

WHY DO WE DO
WHAT WE DO?

TO CREATE A MORE SUSTAINABLE WORLD
EVERYDAY EVERYWHERE WITH OUR
INTELLIGENT HEATING & CONTROL

Viegand Maagøe

Thank you for listening!

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Volatile and Heat Recovery System Design - Labotek Case Study

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A team from Labotek A/S and Technical University of Denmark (DTU Mechanical Engineering Department) work together to develop an idea from concept to final product called "Volatile and Heat Recovery system (V-EHR)". A concept for reusing contaminated hot air from extrusion process for heating and dehumidification of plastic granular.

In the following sections, first, the crucial role of the proposed system on reduction of energy in plastic industry is discussed; then the proposed concept is briefly introduced. This is followed by the description of the methods used for the case study and the final outcomes of the project.

Background

Plastic production is an energy intensive process with a high level of heating and cooling demand. Recently increasing energy costs and environmental regulations are drawing attention towards shifting from pure economic emphasizing to both economic and sustainability emphasis (optimization of energy and reduction of wastes) in this sector.

Drying of plastic granulate is a key step that is required in many industries to guarantee high quality of the final products. Inadequate removing of moisture and other volatiles contained in injection-molding plastic materials, prior to entering the plastic mold injection machine, causes problems such as formation of air pockets in the product, consequently serious degradation of the final product quality. Therefore, it is highly required to dry such materials in a dryer through which a flow of heated air is passed. Several hours of drying are usually needed, and a considerable amount of energy is used during the drying process. In addition, moving towards sustainable plastic production which will substitute oil-based materials with environmentally friendly bio-based plastic products that absorb more humidity, may lead to even further requirement for drying applications in the future [1].

In many applications, the plastic needs to be heated up, but only to a relatively low temperature level of about 80 °C to 90 °C. Hence, recovering heat from other available streams in the whole plastic injection processes can cover some or all of the required energy in the dryers which has been provided so far externally, consuming expensive electricity, and correspondingly reduce waste heat from the other parts.

Labotek A/S supplies equipment designed for crystallization and for drying, transport, dosage and storage of free flowing plastic granules and powdered materials with a wide range of applications in different industries. They are a leading provider of ancillary and centralized systems, all developed based on the new technologies and designed to optimize and consequently reduce the energy consumption in the plastic industry. Thus, Laboteks' drying solutions and process integration technology may benefit the industry to achieve a significant energy savings.

Proposed concept by Labotek:

Figure 1 illustrates a proposed concept by Labotek A/S called "Volatile and Heat Recovery System V-EHR)". The proposed system will provide the possibility of recovering the hot air from plastic pipe extruder. That means regeneration of initial energy from extrusion process to pre-heat the air used in the drying machinery.

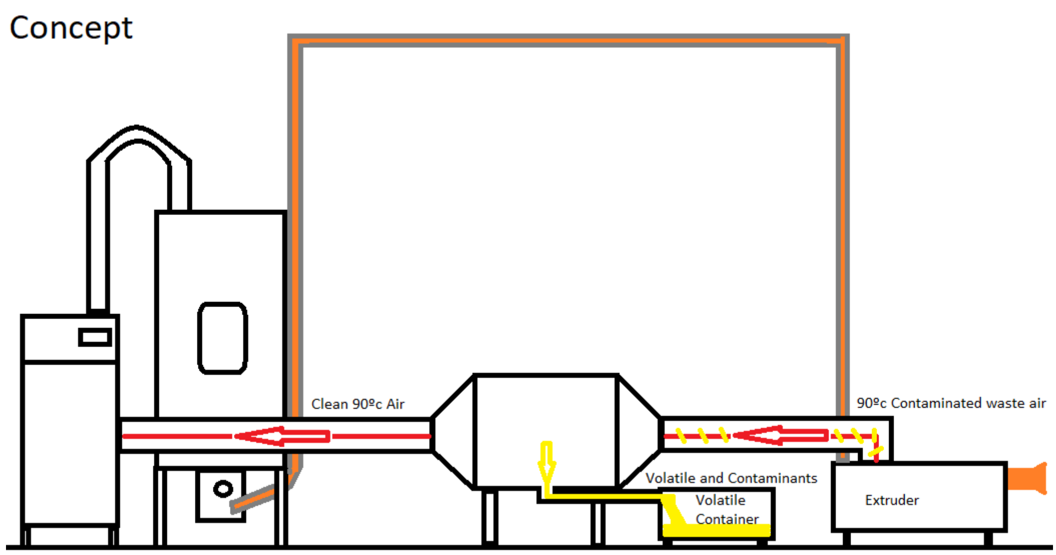

Figure-1: Proposed concept by Labotek A/S called "Volatile and Heat Recovery System (V-EHR)"

As it can be seen from Figure 1, 90 °C hot air coming out of the extruder has a high potential to be used for heating of the plastic granulate in the drying machinery, before entering the plastic mold injection machine extruder. However, the big challenge here is the small amount of additives in the air coming from extrusion processes that will not let it be reused directly in the drying machinery. In order to clean the contaminated air form extrusion processes, the air should be cooled down to below 30 °C until volatiles change to liquid phase and extracted. As a next step, the clean air will be heated up by heat recovery of the initial energy from extrusion process and directed to the drying machinery.

The proposed system can provide multidimensional advantages such as:

- Reducing the total energy consumption, consequently reducing CO_2 emission in the use-phase. This can reduce the global warming effect which has been one of the most critical environment-related problems for the international community for decades [2,3]
- Reducing the energy and resources consumption, consequently lowering the total costs, and increasing the production capacity.
- Providing the possibility of offering not only a product, but also a flexible solution that can be optimally adopted, and integrates the offered product to the existing facilities. This means a minimum changes requirement for implementing such systems in the production line, which is favorite of many manufacturer.

Conceptual design

Figure 2 illustrates the drawing of a preliminarily design of the proposed system. As it is shown in Figure 2, the main concept consists of a set of heat exchangers connected in a series and supporting each other in the three following steps to fulfill the required conditions. The aim was to provide three models operating with three different air volume flow rates of 1000 m^3/h, 3000 m^3/h, and 5000 m^3/h, at 150 mbar.

Step 1: The blowing air enters the first heat exchanger, where the heat will be removed and the air temperature will be reduced as much as possible.
Step 2: A cool process water will be used to cool down the air temperature below 30 °C, therefore, extracting the volatile and contaminates and cleaning up the air.
Step 3: The process air will be heated up above 60 °C, by extracting as much of the heat as possible available from step 1.

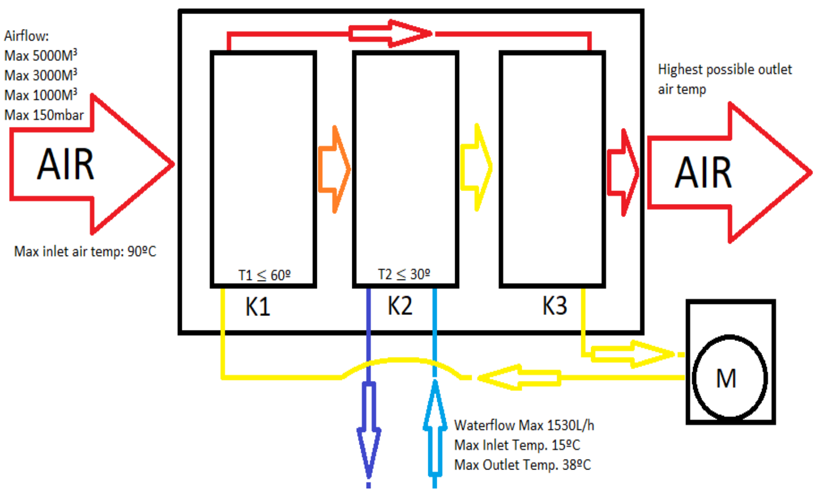

Figure-2: Preliminarily design of the proposed system consists of three heat exchangers connected in a series

Figure 3 shows the 3D configuration of the prototype, corresponding to the design concept illustrated in Figure 2. The presented prototype was designed, built and installed in the final product by Labotek A/S.

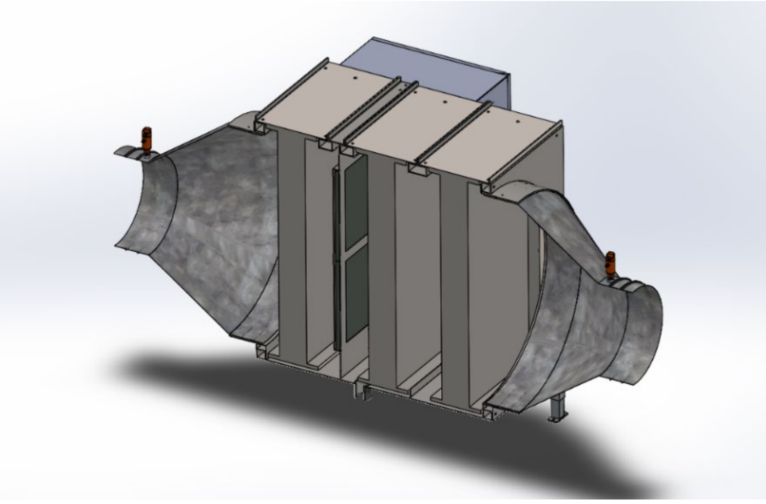

Figure-3: The 3D configuration of the proposed prototype developed by Labotek A/S

Method

This section presents method and concepts used for the modelling, analysis, and evaluation of the proposed concept. First, the required data related to the process and main system components were collected. In the next step, a thermodynamic model based on mass and energy balances of air and water flow in the three heat exchangers was developed to investigate the system performance, followed by the design procedure and selection of the appropriate mechanical components for the system. The target was to reach minimum of 50 % regeneration of initial energy from the extrusion process, and fulfilling of the following required temperature

- Maximum of 30 °C in the middle heat exchanger with the cooling process
- Minimum of 60 °C at the outlet of the third exchanger

For further energy analysis and optimization the possibility of integration of heat pump for utilizing waste heat from extrusion process was evaluated. A previous study on potential for the application of heat pumps in the German industry showed that at a temperature level of 80 °C up to 14 % of the industrial heat demand can be covered by available heat pumps in the market [4].

Simulation models

A complete system model was developed as a tool to assist during the design process. Figure 4 shows the drawing of the system for the two cases direct heat recovery and heat pump integration, which were modeled in Engineering Equation Solver (EES) by DTU Mechanical Engineering.

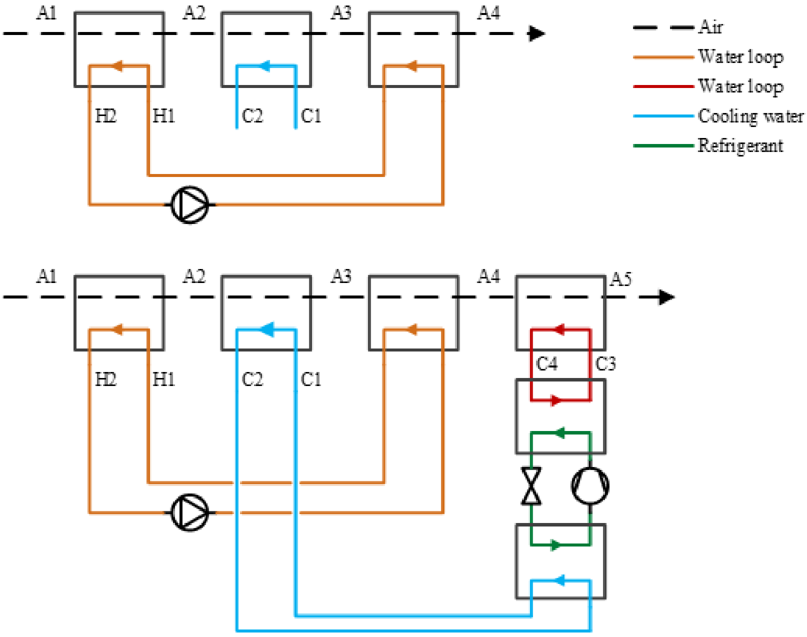

Figure-4: drawing of the system for the two cases (upper) direct heat recovery and (lower) heat pump integration, consists of air and water loops for cooling and heating purposes

The models were based on mass and energy balances, assuming constant air and water mass flow rates through the heat exchangers. The heat exchangers were modelled as described by equation 1, where the condensation of volatiles is neglected, due to the negligible amount of volatile/kg air

$$\dot{m}_{air}\left(h_{air,in} - h_{air,out}\right) = \dot{m}_{watre}\left(h_{water,in} - h_{liq,out}\right) \quad (1)$$

Where $\dot{m}$ is the mass flow rate of the air or water and h is the specific enthalpy of the flow at the inlet (in) or outlet (out) of the heat exchanger.

The size of the heat exchangers was taken into account by considering the minimum temperature differences in the heat exchangers assuming 10 K in the first and last heat exchanger, presented in Figure 4, and 5 K in the middle heat exchanger used for cooling purposes. The pressure drop on the air side was equal to 47 Pa, 43 Pa, and 52 Pa for the first, second and third heat exchanger, respectively. The pressure drop on the liquid side was neglected. The assumed numbers were based on the information provided by heat exchanger supplier. It should be mentioned that the optimal size of heat exchangers is a pure economic parameter, which should be found through optimization of investment and operating costs.

The estimation of power consumption for the heat pumps was based on equation 2, where the coefficient of performance (COP) is estimated based on the Lorenz (COP_{lor}), assuming Lorenz efficiency (μ_{lor}) of 0.6, from equations 3 and 4.

$$P_{\mathrm{comp}} = \dot{Q}_{\mathrm{sink}}/\mathrm{COP} \qquad (2)$$

$$\mathrm{COP} = \mathrm{COP}_{\mathrm{lor}} \times \mu_{\mathrm{lor}} \qquad (3)$$

$$\mathrm{COP}_{\mathrm{lor}} = \frac{T_{\mathrm{sink,lm}}}{T_{\mathrm{sink,lm}} - T_{\mathrm{source,lm}}} \; ; \; T_{\mathrm{sink,lm}} = \frac{T_{\mathrm{sink-out}} - T_{\mathrm{sink-in}}}{\ln\left(\frac{T_{\mathrm{sink-out}}}{T_{\mathrm{sink-in}}}\right)} \text{ and } T_{\mathrm{source,lm}} = \frac{T_{\mathrm{source-out}} - T_{\mathrm{ssource-in}}}{\ln\left(\frac{T_{\mathrm{source-out}}}{T_{\mathrm{source-in}}}\right)} \qquad (4)$$

The Lorenz COP was found by dividing the logarithmic mean temperature of the heat sink by the difference between the logarithmic mean temperatures of the sink and source temperature as is shown in equation 4. In this study, the inlet and outlet of heat sink corresponded to temperatures of A4 and A5 in Figure 4 and the inlet and outlet of heat source corresponds to A2 and A3 presented in Figure 4 respectively, and $\dot{Q}_{\mathrm{sink}}$ was the amount energy used to heat up the airflow from temperature A4 to A5 in Figure 4.

The regeneration percentage is calculated based on equation 5.

$$\mathrm{reg}\ (\%) = \frac{h_{\mathrm{air,out}} - h_{\mathrm{air,0}}}{h_{\mathrm{air,in}} - h_{\mathrm{air,0}}} \times 100 \qquad (5)$$

Where $h_{\mathrm{air,in}}$ is the specific enthalpy of the air at the inlet the first heat exchanger and $h_{\mathrm{air,out}}$ is the specific enthalpy of the air at the outlet of third or fourth heat exchanger for direct heat recovery or heat pump integration cases presented in Figure 4 upper and lower respectively. $h_{\mathrm{air,0}}$ corresponds to the specific enthalpy of the air at 15 °C and pressure at the outlet of the third or fourth heat exchanger, presented in Figure 4 upper and lower respectively.

Outcomes

Results of EES models

Some of the results obtained from EES models are presented in Figure 5 for the two cases of direct heat recovery and heat pump integration. The calculations were made in the form of executable files. The files for the two cases of direct heat recovery and heat pump integration provided to the Labotek look like the ones illustrated in Figure 5. The variables located in the squares in Figure 5 can be easily set to evaluate the system performance for different design and operating conditions.

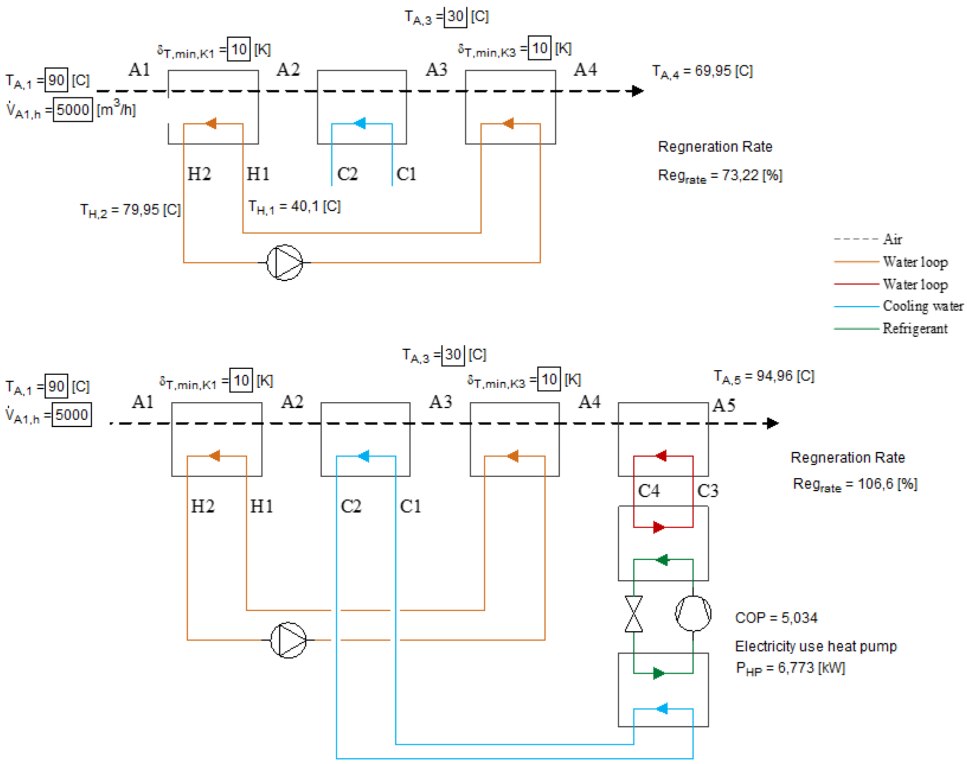

Figure-5: Results obtained from EES model, for the two cases (upper) direct heat recovery and (lower) heat pump integration for 90 °C and 5000 m^3/h inlet airflow

The presented results in Figure 5 show that the proposed system can reach the final air temperature of about 70 °C and regeneration rate up to 73 %, for an inlet air temperature of 90 °C and volume air flow rate of 5000 m³/h. Assuming similar conditions for the case of heat pump integration, the outlet air temperature reaches to about 95 °C corresponds to regeneration rate of 107 %. This is done by consuming 6.7 kW electricity for heat pump compressor, which corresponds to heat pump COP of about 5. The amount of electricity consumption in heat pump will reduce if the required outlet temperature reduces, which is mostly the case for the plastic granulate. As it is explained in the method section, the obtained results are based on assuming a Lorenz efficiency of 0.6; however, for better understanding of the system performance a detailed modeling and analysis of the heat pump is required.

Final product developed by Labotek

Figure 6 shows the photos of product developed by Labotek in Egypt. Labotek has 3 installations with the proposed heat recovery system in a factory in Egypt.

Figure-6: photos of final product developed by Labotek, and installed in a site in in Egypt

Further Development of the final product

The project has been initiated in 2019, and through the collaboration, Labotek has already developed and sold 9 units of the proposed system with direct heat recovery (6 out of 9 was already sold in 2020). Labotek is currently working on further development of the products. Through different versions, changes have been made to control the machine and optimize the regeneration rate. The process was further optimized by introducing an inverter to the blower, and some sensors that can adapt the cooling water usage more accurately. Furthermore, Labotek is currently working on a more advanced control-concept that adapts based on the available energy.

Acknowledgment

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Volatile and Heat Recovery System

Labotek Case Study

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Labotek

- Founded in 1943, Labotek A/S has been a pioneer of high quality, cutting-edge solutions to the plastic industry.
- Labotek A/S is a leading provider of ancillary and centralized systems, all developed on the basis of the new technologies and designed to significantly reduce the energy consumption in the plastic industry
- Labotek supplies equipment designed for crystallization and for drying, transport, dosage and storage of free flowing plastic granules and powdered materials.
- Labotek is a member of the Labotek Group placed in Scandinavia, United Kingdom, Germany and India (worldwide distribution network, contains more than 50 dealers and agents).

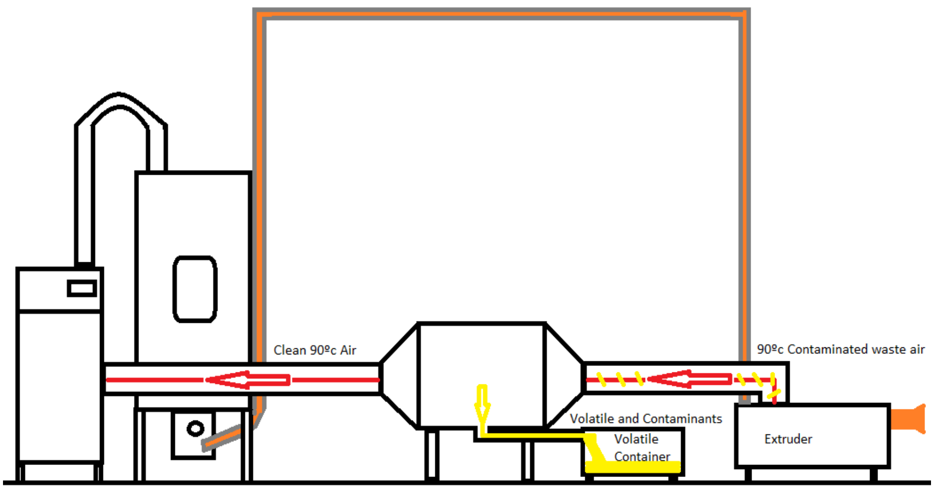
Labotek
Power in Plastics

Source: https://labotek.com/

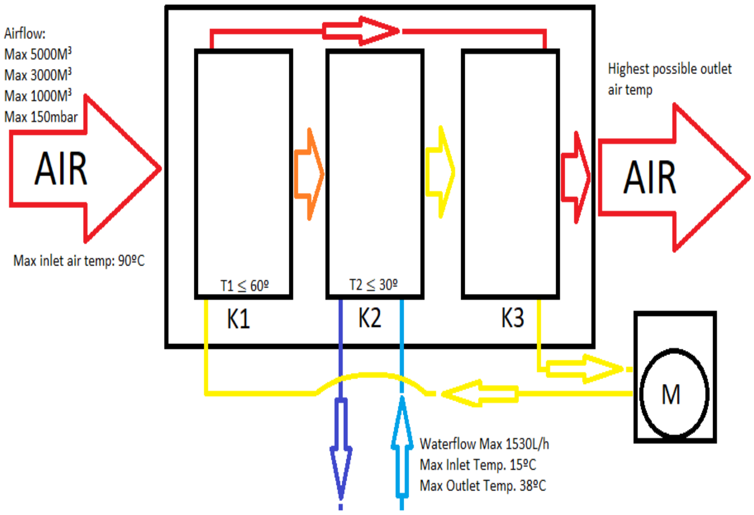
Labotek Proposed Concept

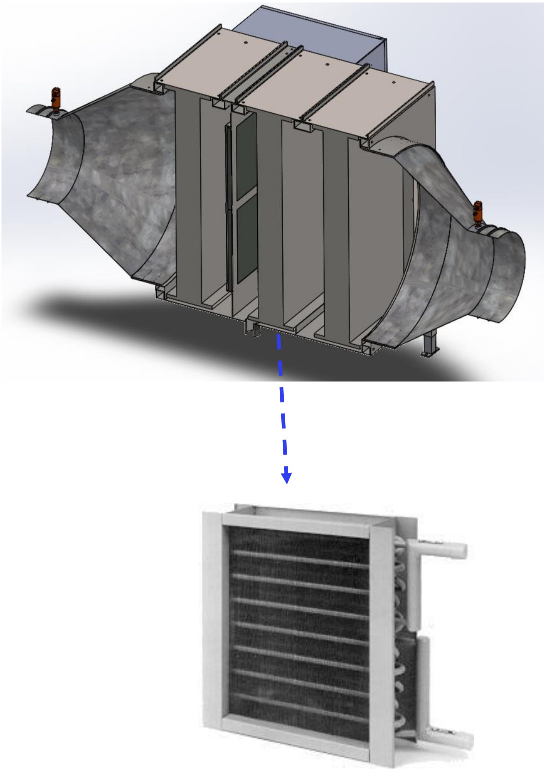
Volatile and Heat Recovery system (V-EHR)

A system that recovers hot air from extrusion process, and regeneration of initial energy to provide warm air for drying machinery



Conceptualization





Background

Drying of plastic granulate is a key step that is required in many industries to guarantee high quality of the final products

The proposed system:

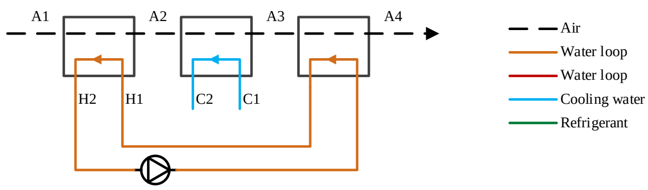
- Reduces of the total energy consumption, consequently reduces CO_2 emission in the use-phase.
- Provides the possibility of offering not only a product, but also a solution that can be optimally adopted and integrates the offered product to the existing facilities

Method

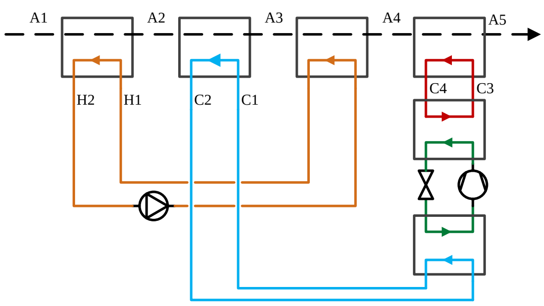
- ➢ Process analysis and data collection
- ➢ Energy analysis
- ➢ Energy optimization
    - » Minimum of 50% regeneration of initial energy
    - » Maximum of 30°C in the middle HEX with cooling process
    - » Minimum of 50-60°C at the outlet
- ➢ Heat pump integration

DTU EES-Model

Heat exchanger model (Direct)

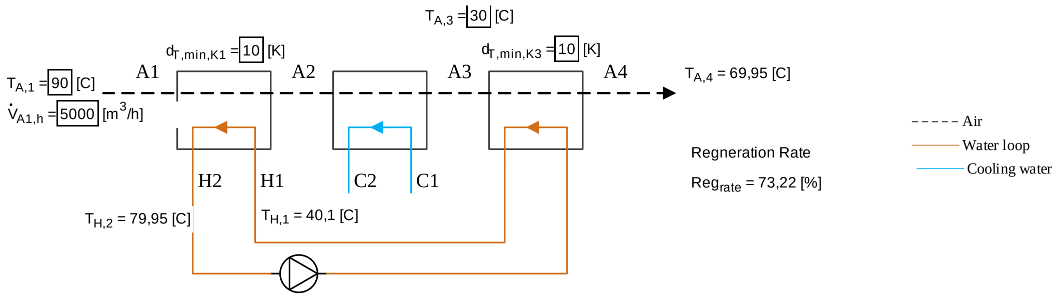


Heat exchanger model (Heat pump)



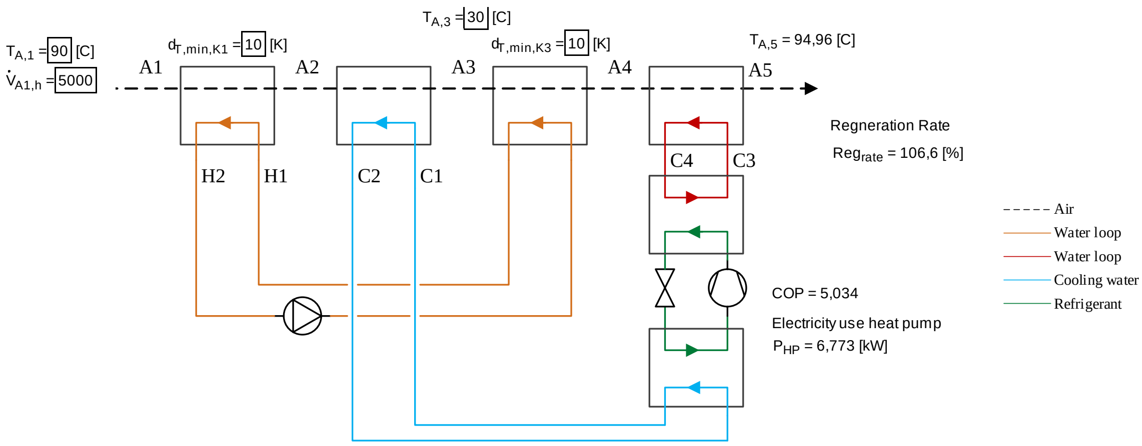
Outcome of DTU EES Model

Heat exchanger model (Direct)



Outcome of DTU EES Model

Heat exchanger model (Heat pump)



Labotek Final Product

3 Installations with heat recovery in Egypt

Further Development of Labotek Product

- Labotek has sold 9 of H-EVR systems (6 in 2020)
- Through different versions changes have been made to control the machine and optimize the regeneration rate
- The process is optimized by introducing an inverter to the blower, and some sensors that can adapt the cooling water usage more accurately
- Labotek is currently working on a more advanced control-concept that adapts based on the available energy

Contacts and Acknowledgment

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DTU: Nasrin Arjomand Kermani, Fabian Bühler, Brian Elmegaard (be@mek.dtu.dk)

February 22nd, 2021

Webinar: Electrification of processes and technologies in the Danish industry

ELECTRIFICATION OF THE HEAT SUPPLY THROUGH HEAT PUMPS

Application in the brewery industry

Alessandro Mattia

RESEARCH GOALS

"Together Towards ZERO" sustainability programme

- - 50% CO_2 by 2022 → carbon neutral by 2030
- 100% electricity from renewable sources

ZERO CARBON FOOTPRINT

→ *Electrification of the heat supply in the brewhouse*

→ *Reduction in natural gas consumption*

CASE STUDY

Existing brewery of Carlsberg Group → Standardized process for broader applicability

METHODS

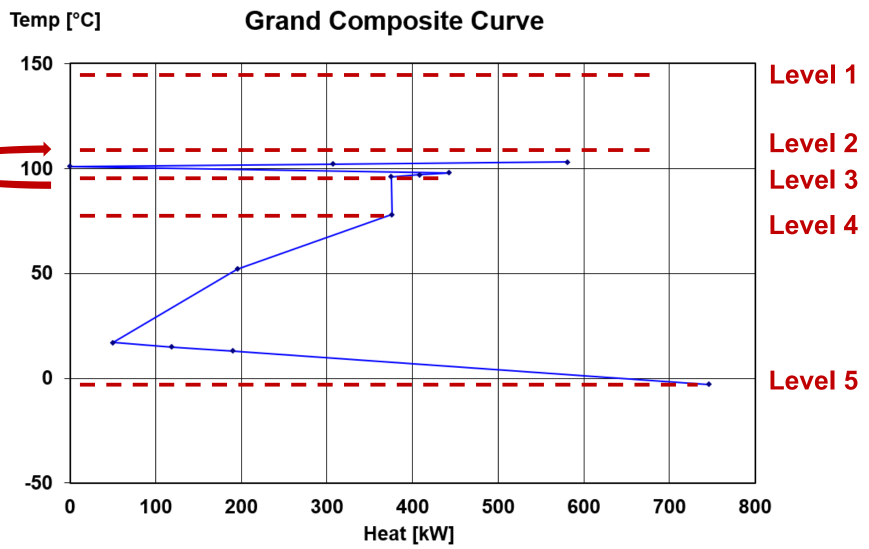
1) Pinch analysis TAM & TSM
2) Integration of heat pumps
   - Open cycle and closed cycle
   - Different heat sources

TIME AVERAGE MODEL

- ➢ Potential energy savings → 59%

CURRENT STEAM SUPPLY

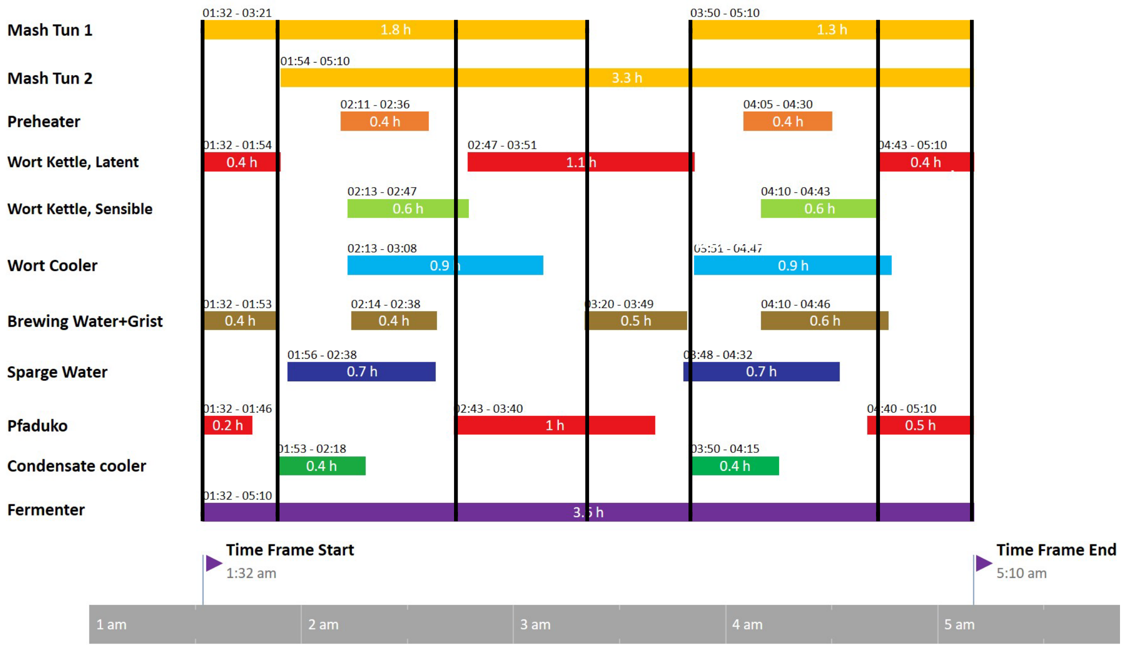
MVR



HTHP

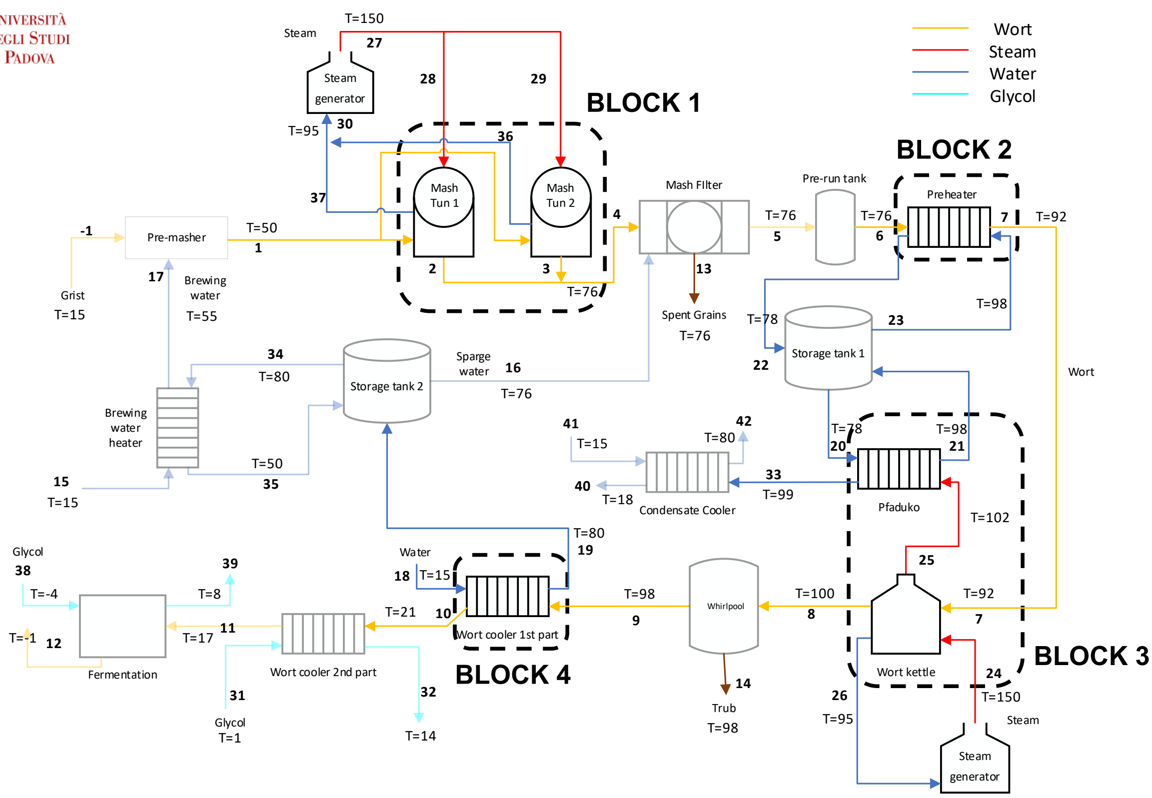
- Internal heat source (wort cooler)
- External heat source (DH, outside air)

TIME SLICE MODEL



- 6 slices
- Energy savings: 2.38%

1. Current natural gas consumption > Natural gas w\o heat storage
2. <u>Good heat recovery hard to achieve</u>



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CONFIGURATION 1A: MVR & HTHP

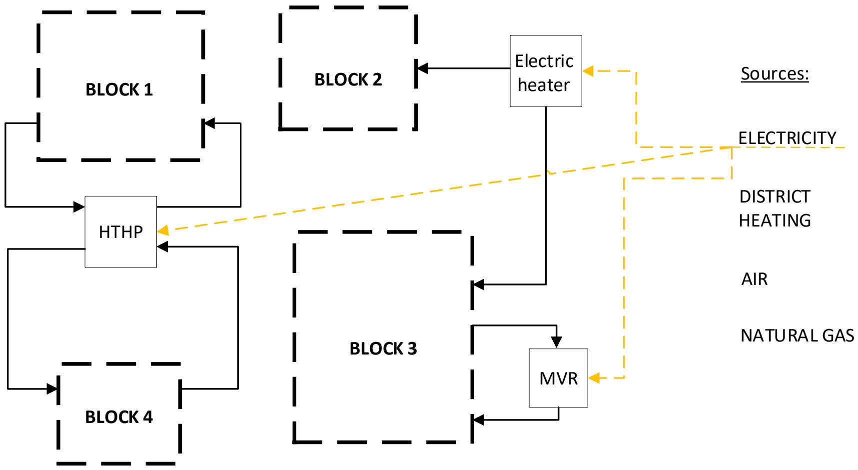
- Heat source → water from wort cooler
- Electric heater to supply the lack of heat

⬇

Complete elimination of steam supply from natural gas

⬇

CO_2 reduction: -1.8 million kg/year



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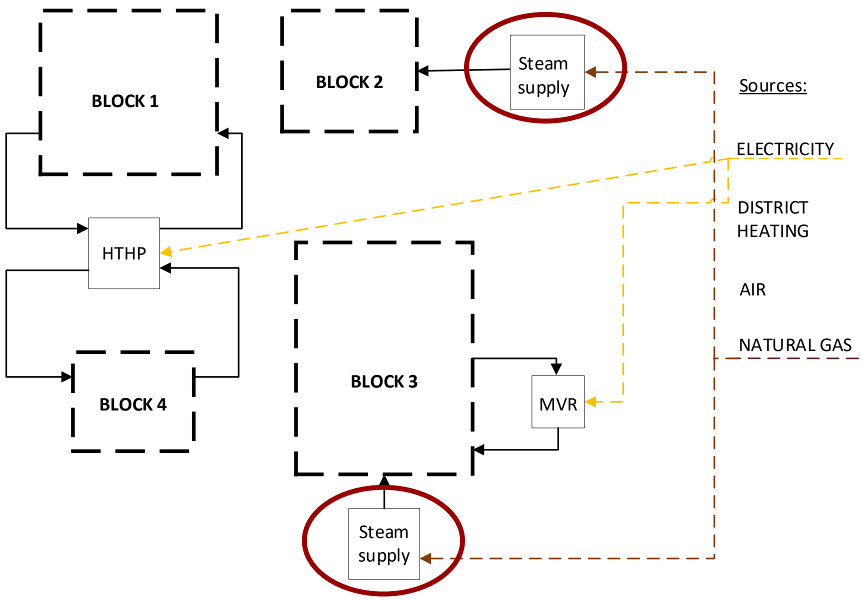
CONFIGURATION 1B: MVR & HTHP

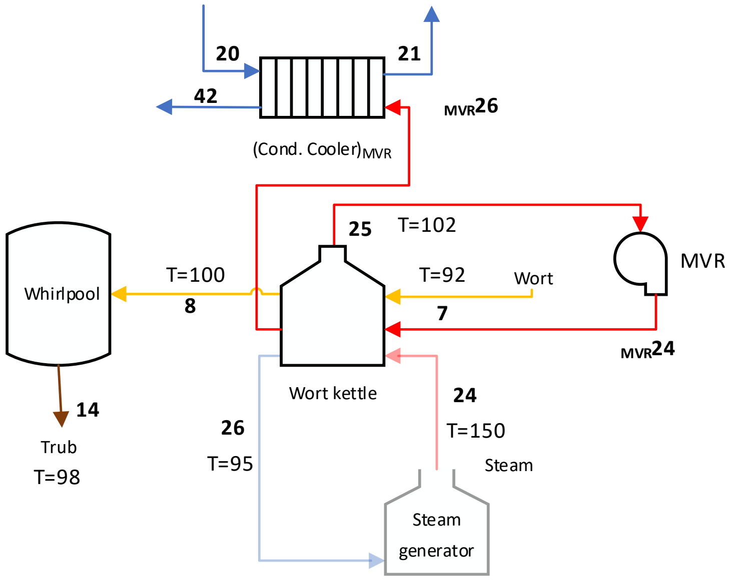
- Heat source → water from wort cooler
- No electric heater

⬇

CO_2 reduction: -792,000 kg/year



MECHANICAL VAPOUR RECOMPRESSION



PERFORMANCES

- $\dot{W}$ = 19.15 kW
- COP = 28.53
- Lift = 8°C

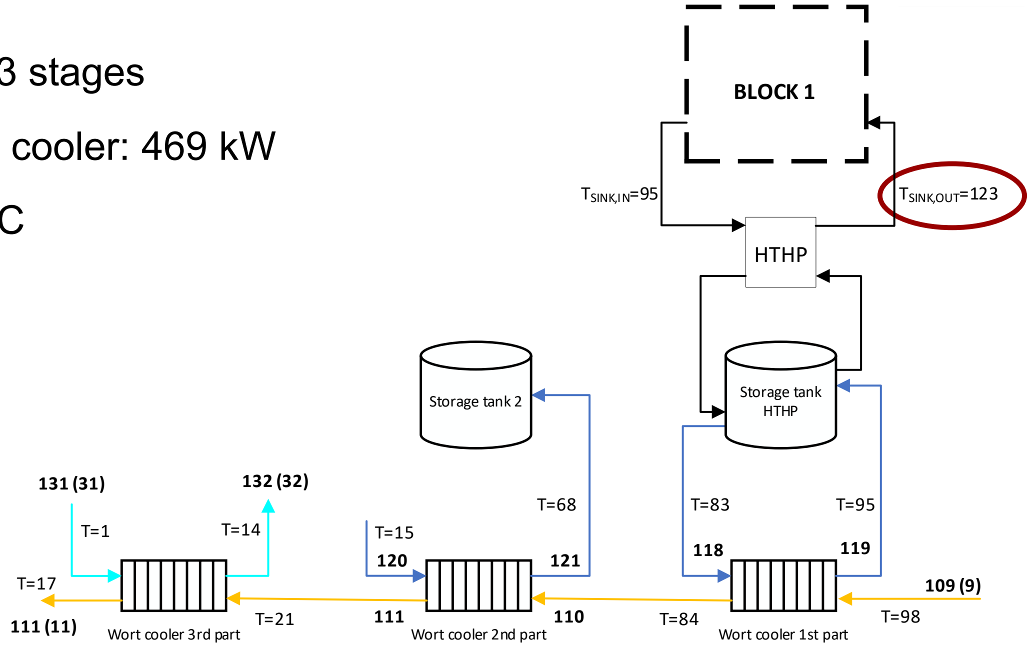
Heat partially recovered at the pfaduko

HIGH TEMPERATURE HEAT PUMP

- Wort cooler division → 3 stages
- Lack of heat at the wort cooler: 469 kW
- Water recovered at 68°C

PERFORMANCES

- $\dot{W}$=104 kW
- COP=5.49



DTU

Università degli Studi di Padova

CONCLUSION

Carlsberg Group

GOALS

- ✓ Reduction in CO_2 emissions (target → <u>more than 80 breweries</u>)
- ✓ Insight on the consequences of HP integration

ZERO
CARBON
FOOTPRINT

→ *Reduction in natural gas consumption (<u>1764 GWh in 2019</u>)*

→ *Electrification of the heat supply in the brewhouse*

DTU

Università degli Studi di Padova

Carlsberg Group

THANK YOU

Integration and optimization of a reversed Brayton cycle coupled with renewables and thermal storage in an oil refinery

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Keywords:

R-744, Reversed Brayton Cycle, Energy mix optimization, Electrification, Industrial processes

Introduction

As greenhouse gas emissions from fossil fuel combustion are one of the main factors for global warming, the EU has imposed policies and regulations on climate and energy [1]. In the 2030's climate and energy framework, the goal is set to 40% reduction in greenhouse gas emissions from the level of those in 1990 [2]. Denmark has even more ambitious targets. The Energy Strategy of 2050 aims at Denmark being completely independent from fossil fuels [3]. For that reason, continuous research is ongoing for the removal and replacement of fossil fuels.

The share of renewable energy technologies in the energy mix has increased over the past years, mainly in electricity production. Society is gradually moving towards a future with electrified systems based on renewable sources. Concerning heat production, heat pumps are a highly attractive for electrification, which could substitute fossil fuels based boilers and furnaces. On an industrial level, there is a large demand in heat in high temperatures over 100 °C, which designates the potential of integration of High-Temperature Heat Pumps (HTHPs) [4]. Because of high temperature lifts accompanied with high temperature applications, the energetic performance of heat pumps deteriorates. Therefore, HTHPs could be considered in combination with large shares of renewable electricity sources. The renewables enable low levelized cost of electricity, which would improve the economic feasibility of the heat pump system.

In this study, the potential of a HTHP project is evaluated from a technoeconomic perspective when coupled with renewable electricity sources and thermal storage. Through optimization, the capacities of the considered technologies are determined, and the project is compared with conventional combustion technologies and electric boilers [5]. The concept is applied to the case study of an oil refinery and conclusions were extracted for such an industry.

Case Study

Crude Oil preheat trains are designed to reduce energy in terms of fuel combustion. Petroleum recovered from a reservoir is, at first, desalted and then heated in preheat Heat Exchanger Network (HEN). In a series of heat exchangers, heat from distillation cuts is transferred to crude oil, which is then heated in the Atmospheric Distillation Unit (ADU) furnace to a temperature close to 360 °C before it enters a fractionating column operating close to atmospheric pressure, wherein fractions with different boiling points are separated off. The remnants of atmospheric distillation are further heated and distilled in vacuum [6].

In this project, the furnace before the ADU is to be replaced with HTHPs leading to partwise electrification of the crude preheat train process and the removal of its most polluting components. The revamping of the heating process of crude is considered to be applied to an already retrofitted site, from where three crude oil and several distillation fraction streams were extracted and comprised subjects of the sink and source side of the heat pumps respectively [7].

Methods

Heat Pump Integration Scenarios

For heat pump integration, alternative cases were distinguished and investigated. Two following scenarios were formulated; the crude is heated to the (1) desired temperature (≈360 ˚C, 34.4 MW) and (2) to a lower temperature (=300 ˚C, 16.96 MW) before it enters the ADU. The latter is formulated as lower temperature lifts will result on a better energetic performance and additionally the temperature at the outlet of the compressor is going to be lower. Also, heat exchangers are more susceptible in fouling as crude is heated in higher temperatures [8].

For each scenario stated, different sub-scenarios were created, depending on the number of heat pumps and how they are integrated in order to transfer heat from distillation cuts to the crude. In sub-scenario ‘A’, one heat pump is integrated, where heat is supplied indirectly from fractions to crude. Through a HEN distillation, fractions increase the temperature of a heat transfer medium that acts as source in the HTHP. On the sink side, heat is received from another heat transfer medium and is then applied to the crude streams through another HEN. The chosen Heat Transfer Fluids (HTFs) were mineral oil for source and solar salt for sink, as they are considered to be relatively cheap and stable at the temperature levels studied [9]. In sub-scenario ‘B’, there are three heat pumps, a distillation fraction stream acts as source at each HTHP and the heat is applied at the sink immediately to the crude. Lastly, ‘C’ is similar to ‘B’. There are six heat pumps and the crude streams are divided before they enter the HTHPs, where distillation fraction streams act as source.

Reversed Brayton Cycle

Because of high temperature lifts, there is a high-pressure ratio in HTHPs. That enables the mounting of a turbine in the expansion process so that work is recovered. For the recovered work to be utilized, the turbine is mounted on the same shaft as the compressor. The cycle will operate at supercritical conditions to ensure gas phase of the working fluid. R-744 was chosen, as it is a natural refrigerant with stable operation at required temperatures that also has good heat transfer properties. In the cycle there is also an Internal Heat Exchanger (IHX) which ensures that the working fluid is at appropriate temperature levels to receive and deliver heat at the source and sink respectively.

The HTHPs were designed assuming the isentropic efficiency of the compressor and turbine, as well as the pinch temperature at the source and sink, while the Coefficient Of Performance (COP) was optimized. For optimization of the COP the decision variables were the low and high pressure of the cycle and the degrees of superheat after the expansion process [10].

Heat Storage Integration

Due to very large requirements in heat demand in industrial sector that could be covered by HTHPs, there could be potential on dimensioning the heat pump in an increased capacity and couple it with a heat storage system in order to benefit from the time variance of electricity prices. For this integration, a two-tank configuration was considered in both source- and sink-side.

This would only be applicable in sub-scenario ‘A’, where heat is transferred from distillation cuts to crude through HENs. As the HTHP operates at levels above the heat demand requirements, part of mass-flow of HTFs will flow through the HENs to cover the demand, while the rest will accumulate on the Low-Temperature (LT) and High-Temperature (HT) tanks on the source and sink side, respectively. If the HTHP operates at levels below heat demand, HTF will flow from the aforementioned tanks to the HEN and then back to the HT and LT tanks of the source- and sink-side.

Energy Mix Optimization
Cost models were developed concerning reversed Brayton cycles, wind turbines, photovoltaics and heat storage and were combined with weather data and electricity prices from grid time series in order to formulate the optimization problem. The problem was of linear programming and was implemented in GAMS software [10]. Aim of the programming was the minimization of Levelized Cost of Heat (LCOH), while the optimum capacities of the considered technologies were determined.

Results

The average optimized COP of HTHPs for each scenario and their respective sub-scenarios are depicted in Figure 1. The COP is rather low due to high temperature lifts. The sub-scenarios including more heat pumps most likely designate higher COP, because of better utilization of high temperature distillation fraction streams.

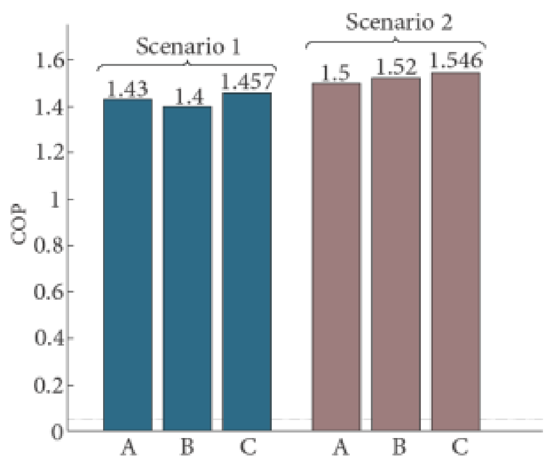

Figure 1. Average optimized COP of Sub-Scenarios

Although the COP is higher in these cases, after optimization of the energy mix capacities and the extraction of the LCOH, the tendencies are different. Due to economy of scale, introducing more heat pumps will lead to higher investment costs and the LCOH of Sub-scenario ‘A’ is lower, even though there are additional costs for the HENs. As that, only sub-scenarios ‘A’ were selected for further investigation. The LCOH values are depicted in Figure 2.

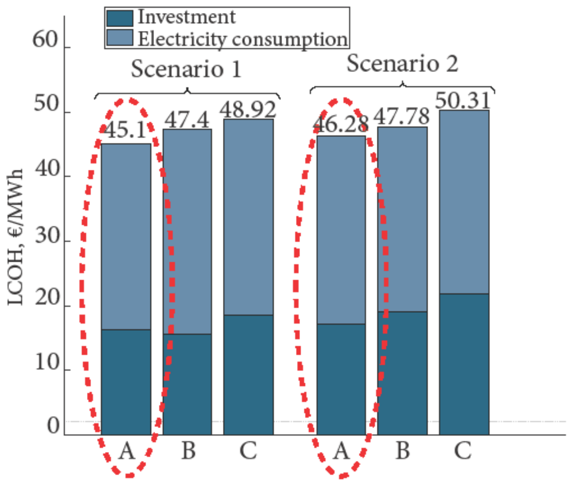

Figure 2. LCOH comparison between sub-scenarios

A comparison of the LCOH of the chosen configuration for each scenario with conventional technologies could be observed in Figure 3. The LCOH will fluctuate between 44 €/MWh and 46 €/MWh, indicating that a LCOH higher than that value for conventional technology will result to a feasible HTHP project. According to those, HTHPs are economically superior to electric and biogas boilers. Although the former may have low investment, it has worse economic performance due to larger electricity consumption, while the latter has very high prices for procurement. The LCOH of natural gas and biomass is of lower value, indicating economic inferiority of HTHPs even when considering the Energy Savings Scheme in Denmark as subsidy [12].

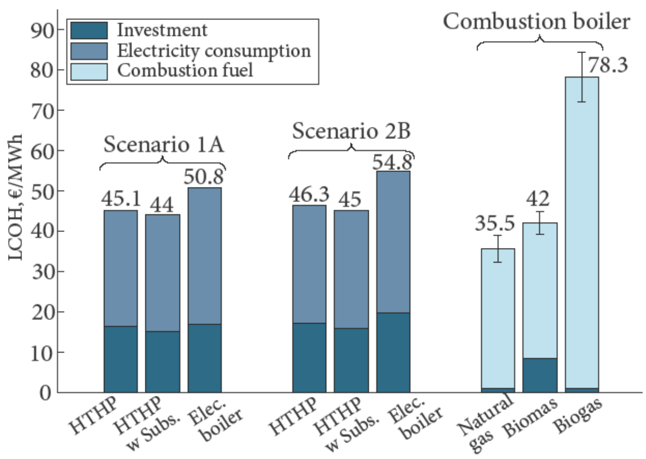

Figure 3. LCOH of HTHPs with and without subsidy and of conventional technologies

Yet, considering projected increases in both biomass and natural gas prices and taxation, in the future there is potential of HTHPs to become more competitive and viable.

The aforementioned results refer to an optimized energy mix. For each scenario the capacities are given in Table 1 and Table 2, along with the COP and the renewable penetration. Wind turbines are chosen in both scenarios and they are coupled with heat storage is scenario 1 and with PVs in scenario 2.

Table 1. Optimal Energy Mix for scenario 1A

TECHNOLOGY	CAPACITY
HTHP	39.6 MW
Wind turbines	28 MW
Heat storage	117.8 MWh
Heat demand	34.4 MW
COP	1.429
Renewable Penetration	37%

Table 2. Optimal Energy Mix for scenario 2A

TECHNOLOGY	CAPACITY
HTHP	16.96 MW
Wind turbines	10.5 MW
PVs	3.8 MW STC
Heat demand	16.96 MW
COP	1.5
Renewable Penetration	34%

Conclusions

This work analysed the techno-economic feasibility of reversed Brayton cycles in an oil refinery and it was concluded that configurations with higher amount of heat pumps introduced high investments and resulted in worse economic performance in terms of economic feasibility. The energy technologies mixture optimization designated that all considered technologies are eligible for application. Wind turbines consist a permanent choice of optimization algorithm, while the choice of heat storage was very much dependent on the COP and the heat demand. PVs consisted mostly a filler option to wind turbines. HTHPs were demonstrated to be superior to electric and biogas boilers, but the contrary when compared to biomass and natural gas boilers. Although they seem not that competitive to those boilers, cost projection of these fuels points that HTHPs would be more viable in the future.

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Integration of a Reversed Brayton Cycle coupled with Renewable Energy Systems in an Oil Refinery

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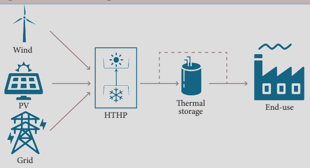
[1] Technical University of Denmark, [2] Danish Technological Institute

INTRODUCTION

Greenhouse gas emissions are one of the main factors for global warming. Denmark contemplates to be a future completely independent of fossil fuels by 2050. For replacement of fossil fuel technologies, heat pumps consist an attractive alternative as they can be efficiently operated with renewable electricity. The demand on high temperature heat in industries necessitates focus on research in the field of High-Temperature Heat Pumps (HTHPs).

OBJECTIVE
The evaluation and optimization of a concept of HTHPs operating with a combination of renewable electricity sources to replace current fossil fuel furnaces in an oil refinery.

APPROACH
Wind turbines and photovoltaics (PVs) along with the grid were considered to supply electricity to HTHPs, combined with heat storage, which could allocate electricity consumption to time steps where it is cheaper.

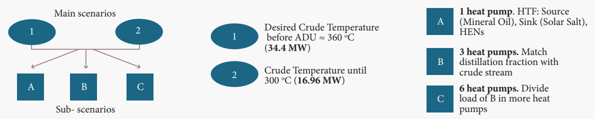


CASE STUDY

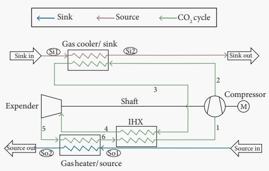
Oil and gas industry is very energy consuming since large amounts of heat are needed to increase the temperature of crude oil in high levels for the distillation to happen. Before atmospheric distillation, crude is heated in a furnace. Aim of the study was the replacement of the furnace before ADU with HTHPs.
Three crude oil streams, to be heated, were subject of the source side and several distillation fraction streams were identified to provide heat at the source side.
The crude oil and distillation fraction streams were selected after a retrofit was applied to preheat network.

METHODS

HEAT PUMP INTEGRATION SCENARIOS

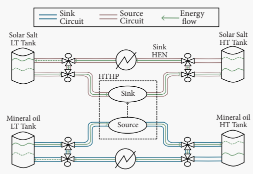


REVERSED BRAYTON CYCLE



- Large temperature lift leads to high pressure ratios. There is potential in mounting a turbine in the same shaft as compressor and recover work in the expansion process.
- The Internal Heat Exchanger (IHX) exists so that the working fluid is at the appropriate temperature levels to receive or extract heat at the source and sink respectively.
- R744 is utilized as refrigerant. Natural refrigerant with stable operation in transcritical conditions and good heat transfer properties.
- Coefficient of Performance is optimized with low and high pressure and degrees of superheat after expansion as decision variables.

HEAT STORAGE INTEGRATION



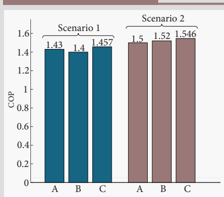
- Two tank storage configuration on both source and sink side with a low and high temperature tank.
- Applicable in Sub-Scenario A only where there are heat transfer mediums on each side.
- For heat storage integration, the heat pump should have capacity higher than the nominal requirements in heat demand.

ENERGY MIX OPTIMIZATION

OBJECTIVE → Maximization of feasibility index/Minimization of Levelized Cost of Heat (LCOH).

DETERMINATION → Optimum capacities of wind turbines, PVs, HTHPs and heat storage.

RESULTS

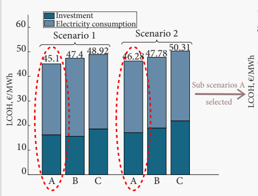


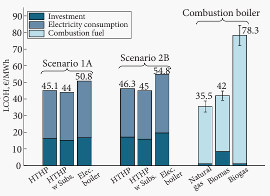
SCENARIO 1A

TECHNOLOGY	CAPACITY
HTHP	39.6 MW
Wind turbines	28 MW
Heat storage	117.8 MWh
Heat demand	34.4 MW
COP	1.429
Renewable Penetration	37%

SCENARIO 2A

TECHNOLOGY	CAPACITY
HTHP	16.96 MW
Wind turbines	10.5 MW
PVs	3.8 MW STC
Heat demand	16.96 MW
COP	1.5
Renewable Penetration	34%





For an optimized average COP, configurations with more heat pumps may provide a better COP.
Sub-Scenarios A, meaning only one heat pump, have the lowest LCOH and only those were further investigated. HTHPs were found to be economic superior to biogas and electric boilers, but demonstrated worse economic performance in comparison with biomass and natural gas.
The two scenarios designated a different optimal energy mix. Wind turbines were chosen in both cases. Heat storage is chosen as the ratio of heat demand to COP is getting larger. Photovoltaics consist a filler option.

CONCLUSIONS

Configurations with higher number of heat pumps introduced high investments and resulted in worse economic performance.

Wind turbines, PVs and heat storage are all eligible for application in HTHP project when aiming in feasibility index optimization.

HTHPs were designated to be superior to electric and biogas boilers, but the analysis showed them to be inferior to natural gas and biomass boilers. Expected future increases, though in both these fuels indicate that HTHP projects would be more viable in the future.

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