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

Final Report

Elmegaard, Brian; Arjomand Kermani, Nasrin; Bühler, Fabian; Nguyen, Tuong-Van ; Bergamini , Riccardo ; Zühlsdorf, Benjamin ; Dupond Holdt, Frederik; Müller Holm, Fridolin; Sandstrøm Petersen, Morten; Helk, Andreas

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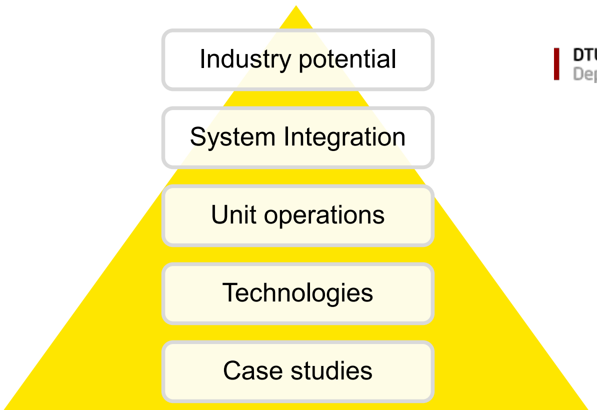
Elforsk project 350-038

Final Report



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Department of Mechanical Engineering

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energy people

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ELFORSK

Labotek

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

Final Report
March 2021

By
Brian Elmegaard, Nasrin Arjomand Kermani (DTU Mechanical Engineering), Fabian Bühler (Energistyrelsen), Tuong-Van Nguyen (EPFL École Polytechnique Fédérale de Lausanne), Riccardo Bergamini (GEA), Benjamin Zühlsdorf, Frederik Dupond Holdt (Danish Technological Institute), Fridolin Müller Holm, Morten Sandstrøm Petersen, Andreas Helk, Niklas Bagge Mogensen (Viegand Maagøe), Peter Jessen Jürgensen, Lars Ingolf Hansen (Labotek), Peter Munk, Emil Lundager Godiksen (SAN Electro Heat), Vegard Hetting, Esben Jacobsen (CP Kelco)

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.

Contents

1 Executive Summary

1.1 Introduction

Denmark's goal of achieving a future energy system based solely on renewable energy by 2050, and reaching 70 % reduction of greenhouse gas emission in 2030, requires that the energy supply is converted to be based on electricity from renewable sources – wind power in particular, and accordingly is *electrified*. At the same time, energy use should be reduced, to support conversion and to use the energy sources best possibly. Industry is one of the most energy-intensive sectors worldwide. It accounts for around 38 % of the world's energy use [13]. In Denmark alone, industry emitted 4,234,000 tonnes of CO_2 in 2014, which exceeds the emission from households, trade and services together [9]. With a fraction of 62 %, the energy use for processes is primarily based on fossil fuels. A further 32 % comes from converted energy, such as electricity and district heating, which is also to some extent fossil-based [8]. Oil refineries, food and beverages as well as the plastics, glass and concrete industries account for the largest share of energy use in the industry, which can be seen in Figure 1.1.

In the food, plastics and cleaning industries, large amounts of natural gas are used for process heat, and a large proportion of the process heat is used at high temperatures. As Figure 1.2 shows 9 % of the industrial natural gas consumption is for food and beverage production.

"Electrification" is described as the substitution of a fossil fuel-based supply with a supply based on electricity. The advantage of an electricity-based heat supply is that it directly uses electricity from renewable energy sources, which may not cause CO_2, NO_x and SO_x emissions, and reduces dependency on fossil fuels. In addition, the processes in industry can be used to provide flexibility in the electricity grid [10]. Another significant effect is that electrification provides the opportunity to rethink the individual processes and their heating needs, as electricity-supplied heat can be made more focused on the actual heat demand in the process, the actual energy service. Thereby

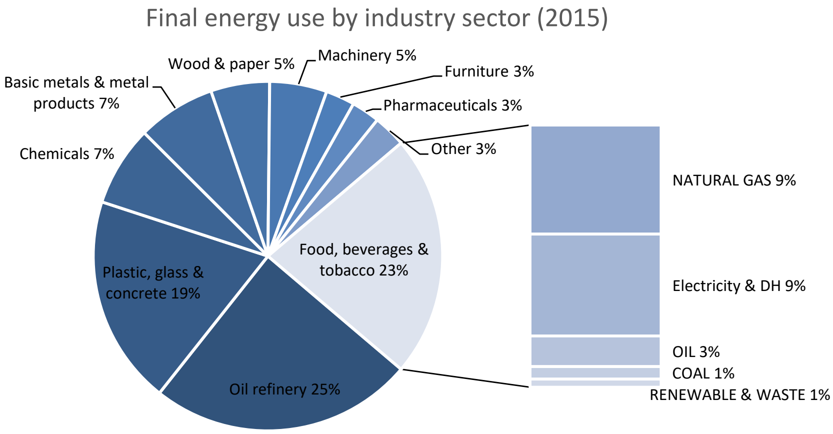


Figure 1.1: Energy use in industry by different sectors and for food and beverages in energy form. Based on data from Statistics Denmark ENE2HA [8]

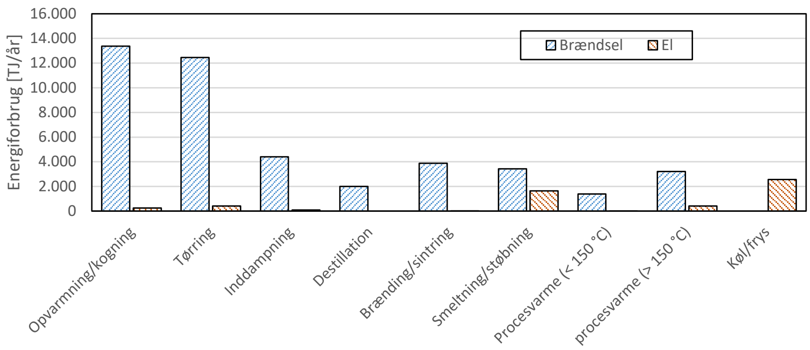


Figure 1.2: Energy use for unit operations in industry in Denmark in 2012 with share of electricity and fuel. Based on [19]

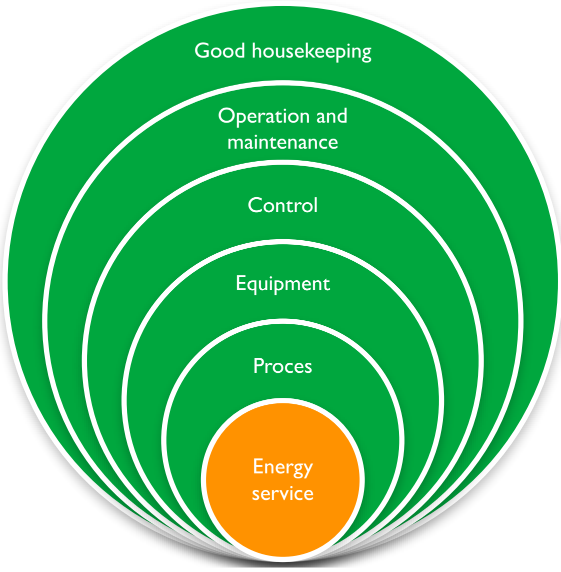


Figure 1.3: Onion diagram for illustration of energy use and efficiency potential in industry [7]

one can reach into the core of the onion diagram as presented in Figure 1.3.

To support this potential, Figure 1.4 shows an exergy analysis based of a complete survey of Danish industry [3]. Exergy is a generalized formulation of energy availability, sometimes referred to as *quality*. Exergy is equivalent to electricity, and accordingly it is a measure of how much of an energy quantity, that may be converted to any other form of energy, like electricity can. Thus, this analysis shows the fact that demand only constitutes the proportion described as a *product*, but the rest of the energy use can theoretically be eliminated by using the energy at the exact exergy level of need. Potentially, energy use can thus be reduced to about a third by using electricity. This mapping and others used for determination of electrification potentials in the work has been based on [2].

In Denmark, Dansk Gasteknisk Center A/S has analyzed the technical substitution potential of natural gas with electricity in industry [18]. The report concludes that 88 % of total natural gas consumption can be converted to electricity-based technology. Processes that cannot be converted are flame-based processes which in Denmark provide an output of 37 MW. In addition, the report states that 75 % of this for high temperature processes and 50 % for low temperature processes cannot be converted from natural gas to electricity.

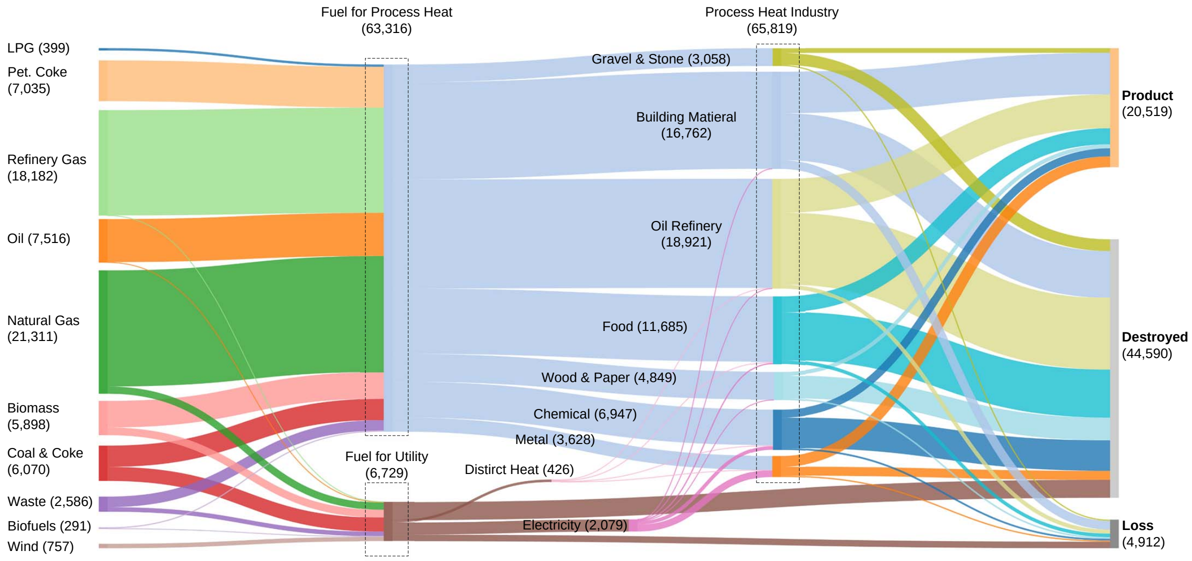


Figure 1.4: Exergy mapping of Danish industry energy consumption which documents the potential for energy savings through electrification [3]

In Europe, research into the electrification of industry has focused heavily on the benefits for industry arising from the reduced electricity prices in the northern European electricity markets from variable renewable energy sources [12]. These prices can already today partly compete with natural gas for heat supply. In addition, research is being carried out in Germany and the Netherlands on how industry can be used to provide additional flexibility in the electricity grid [1].

At the process level, there are not many studies that examine how an industrial company can best convert to a 100 % electric heat supply. An example, however, which shows the potential, is a project from the Netherlands where a concept is being developed for a completely electricity-based slaughterhouse. The project implemented heat pumps to substitute fossil fuels. The result was both financial savings and better operation of the process [16].

Figure 1.5 shows the distribution of heat demand and surplus heat in Danish industry. This illustrates that a large part of the need is from 70 °C to 130 °C, where heat pumps can be used and will have a high COP. The excess heat that can be used as a heat source for heat pumps is over a wide range, but primarily at 20 °C to 50 °C. For the sake of the efficiency of heat pumps, it is important to use heat sources at the highest possible temperature.

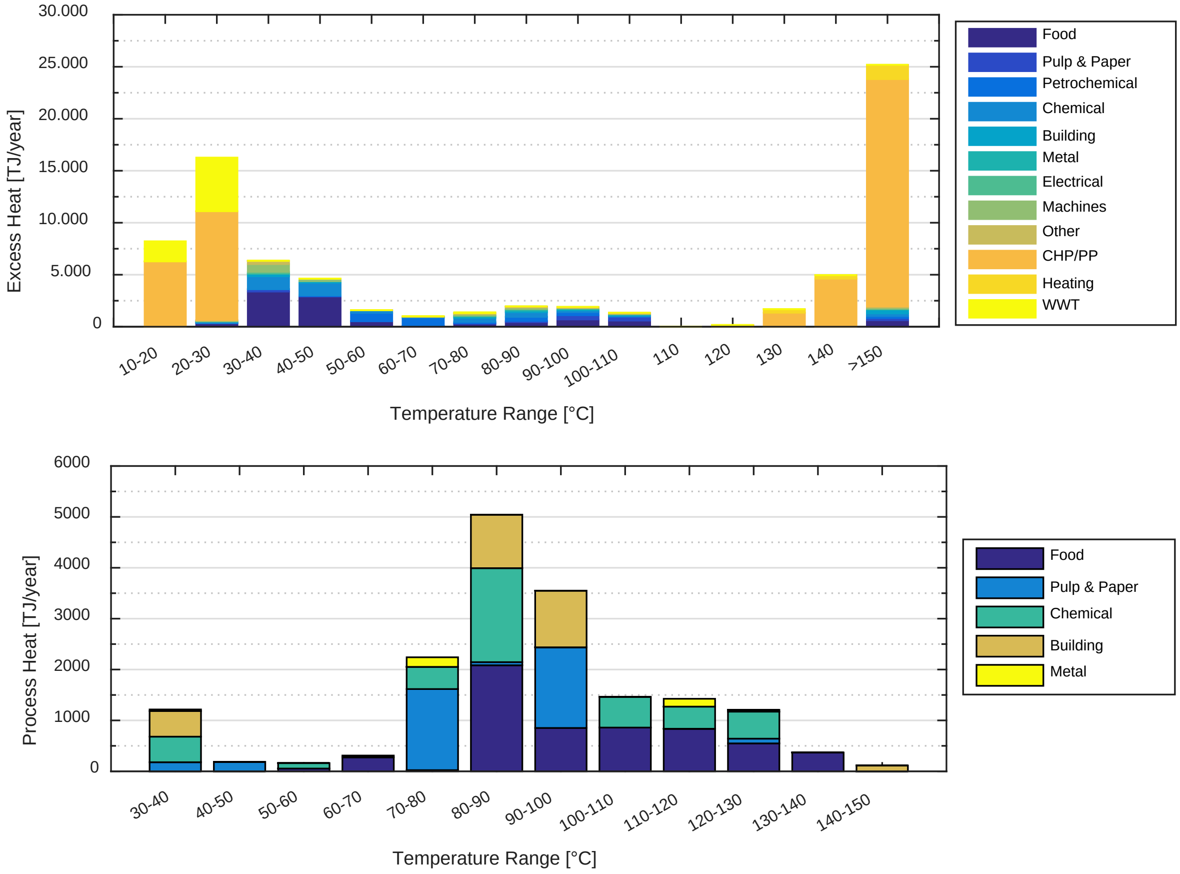


Figure 1.5: Temperature distribution of heat demand and heat surplus in Danish industry [4]

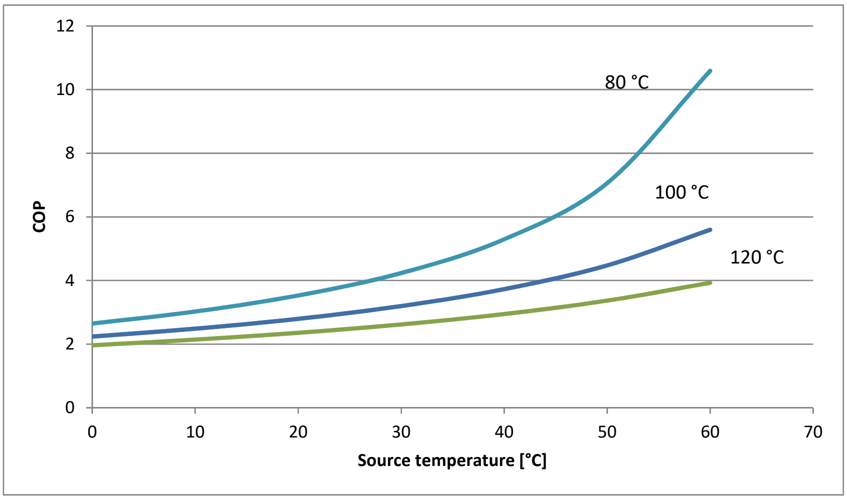


Figure 1.6: COP for heat pumps depending on temperature of heat source and heat demand

This is illustrated in Figure 1.6 where estimated COP values for varying heat sources and heat demand. It is seen that large temperature lifts result in relatively low COP and thus that heat pumps may not be competitive with other solutions, at the same time as the investment will probably not be profitable. Electric heating in these situations will probably be a good alternative.

Figure 1.5 also shows that a significant part is at a much higher temperature, where heat pumps will not be able to be used with current technology. In addition, heat pumps will have a lower COP at these high temperatures, and direct electric heating or hybrid solutions between heat pumps and direct electricity or gas heating can be used.

Already today, more electricity-based heating equipment is being installed in industry in Denmark. Primarily heat pumps have been installed to use surplus heat from processes to supply process heat at a higher temperature level. However, there are limitations in implementing heat pumps. There are economic barriers, as heat pumps must compete with natural gas and therefore only efficient heat pumps will be profitable. In addition, today there are technical limitations for what temperatures and temperature rise heat pumps can deliver. This shows a potential basis for analyzing demands for future heat pump development (e.g., temperature rise or cheaper and more efficient components).

The project has investigated how industrial sectors that are important to Denmark and processes that have challenges in changing supply due to temperature or medium can be electrified. In addition, the technological developments that are necessary to achieve the most efficient electricity-based heat supply and to electrify high-temperature and steam-based processes were identified. The project included modeling, optimization, and analysis of processes in pectin production, milk powder production, brewing, plastics manufacturing, and steam laundry as cases, but with a focus on generalization of the observations to the range of industrial processes.

The potentials of electrification can be exploited in various ways.

Firstly the distinction is between indirect electrification in terms of conversion to fuels produced from power-to-X processes, and direct electrification by converting to electricity as the energy source for process heating. The latter will have higher efficiency and is the focus of the present project.

Direct electrification may be achieved in different ways, which possibly result in energy savings as well as in the significant decrease of CO_2 emissions related to the conversion of the electricity production to be based on non-fossil sources.

Energy savings may be achieved by any means of electrification. The following options may be mentioned:

- by supplying energy directly to the core process for the desired energy service at the right temperature level
- by using heat pumps to utilize excess heat efficiently in the processes
- by converting electric heating processes to heat pump heating
- by heat integration of excess heat and heat demand, which will require electricity for pumping
- by switching from fossil fuels to electric heating
- by using electricity in a flexible way, e.g., in connection with heat storage

1.1.1 Project aim

The main objective of the project was to identify potentials for minimizing energy use in thermal industrial processes and challenges in converting industrial process heat supply from fossil fuels to an electricity-based one in the manufacturing industry.

The main purpose can be divided into the following objectives:

- Identification of opportunities for increasing the efficiency and achieve flexibility of process heat supply in plastic processing, pectin production, brewing, milk powder production and steam laundry as a starting point for cases.

- Identification of requirements, challenges and development potential for technologies, such as heat pumps and electric heating equipment, which can be used with existing technologies, and which technologies should be developed to achieve the objective.
- Test existing electric heating equipment under process conditions for optimized operation and integration of processes.
- Analyze the electrification potential for Denmark's energy system

The following tasks have been conducted:

- Mapping of processes
- Identification of electrification potential
- Modeling of processes and components
- Optimization, integration and electrification
- Pinch analysis in electrification
- Testing of equipment

The project group covered different stakeholders including production industry, component suppliers, consulting engineering, a GTS institute and a university institute.

In addition the project has benefited from collaboration in related projects, and thereby having access to e.g., information on industrial heat pump technology development.

The project group has involved the following:

- DTU Mechanical Engineering: Brian Elmegaard, Nasrin Arjomand Kermani, Fabian Bühler, Tuong-Van Nguyen, Riccardo Bergamini
- Danish Technological Institute: Benjamin Zühlsdorf, Frederik Dupond Holdt, Lars Reinholdt
- Viegand Maagøe: Fridolin Müller Holm, Morten Sandstrøm Petersen, Andreas Helk, Niklas Bagge Mogensen
- CP Kelco: Vegard Hetting, Esben Jacobsen
- De Forenede Dampvaskerier: Simon Birch Torbensen, Christian Lind-Holm Kuhnt
- Labotek: Peter Jessen Jürgensen, Lars Ingolf Hansen
- SAN Electro Heat: Peter Munk, Emil Lundager Godiksen

- Elforsk: Dorte Lindholm

In addition, four master theses have been completed at DTU and have made contributions to case studies in the project.

In the following the main methods and results of the work are presented briefly, while the reports from the individual analyses are included as appendices.

1.1.2 Dissemination

Publications The following publications have been published during the project:

1. Bühler, F., Zühlsdorf, B., Müller Holm, F., Reinholdt, L., & Elmegaard, B. (2018). Electrification of processes in the manufacturing industry Fabian. In C. Melero, & K. Mølhave (Eds.), Sustain Conference 2018: Creating Technology for a Sustainable Society [E-9] Technical University of Denmark. http://www.sustain.dtu.dk/
2. Bühler, F., Müller Holm, F., & Elmegaard, B. (2019). Potentials for the electrification of industrial processes in Denmark. In Proceedings of ECOS 2019: 32nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. See Appendix A.1.
3. Bühler, F., Zühlsdorf, B., Müller Holm, F., & Elmegaard, B. (2019). The potential of heat pumps in the electrification of the Danish industry. In B. Zühlsdorf, M. Bantle, & B. Elmegaard (Eds.), Book of presentations of the 2nd Symposium on High-Temperature Heat Pumps (pp. 51-67). SINTEF. See Appendix A.3.
4. Kousidis, V., Zühlsdorf, B., Bühler, F., & Elmegaard, B. (2019). Integration and optimization of a reversed Brayton cycle coupled with renewables and thermal storage in an oil refinery. In B. Zühlsdorf, M. Bantle, & B. Elmegaard (Eds.), Book of presentations of the 2nd Symposium on High-Temperature Heat Pumps (pp. 235-241). SINTEF. See Appendix C.13.
5. Zühlsdorf, B., Bühler, F., Bantle, M., & Elmegaard, B. (2019). Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C. Energy Conversion and Management: X, 2, [100011]. https://doi.org/10.1016/j.ecmx.2019.100011. See Appendix B.3.
6. Zühlsdorf, B., Bühler, F., Bantle, M., & Elmegaard, B. (2019). Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C. In B. Zühlsdorf, M. Bantle, & B. Elmegaard (Eds.), Book of presentations of the 2nd Symposium on High-Temperature Heat Pumps (pp. 26-37). SINTEF. See Appendix B.4.

7. Bühler, F., Zühlsdorf, B., Nguyen, T-V., & Elmegaard, B. (2019). A comparative assessment of electrification strategies for industrial sites: Case of milk powder production. Applied Energy, 250, 1383-1401. https://doi.org/10.1016/j.apenergy.2019.05.071.
8. Bühler, F., Müller Holm, F., Zühlsdorf, B., & Elmegaard, B. (2020). Energy integration and electrification opportunities in industrial laundries. In Proceedings of ECOS 2020: 33rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. See Appendix C.2.

Reports The project has included a number of individual studies. The reports of these are included in the appendix.

1. Petersen, M.S., Müller Holm, F. (2021). ELIDI – Bottlenecks for electrification. See Appendix A.4
2. Holdt, F.D., Zühlsdorf, B. Elmegaard, B. (2021). Availability of high-temperature heat pumps. See Appendix B.1
3. Kermani, N.A., Petersen, M.S., Mogensen, N.B., Bühler, F., Elmegaard, B., Müller Holm, F. (2021). Electrification of industrial processes with low-to-medium temperature heat demand: CP Kelco case study. See Appendix C.4
4. Kermani, N.A., Helk, A., Bergamini, R., Elmegaard, B., Müller Holm, F. 2021. Energy optimization and electrification of a brewery, Harboe. See Appendix C.6
5. Helk, A., Godiksen, E.L., Müller Holm, F. 2021. Electrification of CP Kelco steam supply. See Appendix C.8
6. Kermani, N.A., Bühler, F., Hansen, L.I., Jessen Jürgensen, P., Elmegaard, B. 2021. Volatile and Heat Recovery System Design - Labotek Case Study. See Appendix C.10

Master theses Master theses developed in relation to the project:

1. Kousidis, V. (2019). Analysis and optimization of high-temperature heat pumps in combination with renewable electricity sources.
2. Petersen, M. S., & Mogensen, N. B. (2019). Electrification of industrial processes with low-to-medium temperature heat demand: Case study of pectin production.
3. Helk, A. (2020). Energy optimization and electrification of brewery.

4. Mattia, A. (2020). Integration of high temperature heat pumps in brewing processes.

Presentations The project has been presented at the following meetings:

1. Brian Elmegaard, Elektrificering af dansk industri, Workshop Få mere ud af dine energidata, 20 March 2018, Teknologisk Institut, Aarhus
2. Brian Elmegaard, Electrification of Danish Industry, IEA IETS 6 April 2018, Amsterdam
3. Fabian Bühler, Elektrificering af dansk industri, Temadag om energieffektivisering i industrien, 8 November 2018, Aarhus
4. Fabian Bühler, Elektrificering i industrien, Møde Miljø- og Energifonden, 8 March 2019, Copenhagen
5. Brian Elmegaard, Elektrificering i industrien, Cleans årsmøde, 27 May 2019, Nyborg
6. Brian Elmegaard, Potentialet for grøn omstilling af industrien ved elektrificering, Elforsk, 20 November 2019, Herning
7. Brian Elmegaard, Potentialet for grøn omstilling af industrien ved elektrificering, Intelligent Energi, 25 May 2020, Viborg
8. Brian Elmegaard, Fra fossile brændsler til el i industrien, Energisynskonsulenternes årlige temadag, 9 December 2020, Online Teknologisk Institut
9. Brian Elmegaard, Udvikling indenfor elektrificering af industriprocesser i Danmark, Webinar Elektrificering af procesindustrien ved højtemperatur-varmepumper, 24 March 2021, Online IDA Energi
10. Brian Elmegaard, Elektrificering af industriens processer, Webinar Intelligent Energi, 12 April 2021, Online

22 February 2021 the project group hosted a webinar with presentations of the results of the work in the project. The collection of presentations from the meeting is also included in the appendix.

This included the following presentations:

1. Bühler, F., Müller Holm, F., Elmegaard, B. 2021. Potentials for the electrification of industrial processes in Denmark. See Appendix A.2.

2. Petersen, M.S. 2021. Bottlenecks for electrification. See Appendix A.5.
3. Zühlsdorf, B. 2021. High Temperature Heat Pumps – Electrification of processes and technologies in the Danish industry. See Appendix B.2.
4. Bühler, F., Müller Holm, F., Zühlsdorf B., Elmegaard, B. 2021. Electrification of a Milk Powder Factory and an Industrial Laundry, pp. 1–17. See Appendix C.1.
5. Bühler, F., Müller Holm, F., Zühlsdorf B., Elmegaard, B. 2021. Electrification of a Milk Powder Factory and an Industrial Laundry, pp. 1–8 and 17–55. See Appendix C.3.
6. Petersen, M.S. 2021. Electrification at CP Kelco. See Appendix C.5.
7. Helk, A. 2021. Energy Optimization and Electrification Study of a Brewery. See Appendix C.7.
8. Helk, A., Godiksen, E.L. 2021. Electrification of CP Kelco Steam Supply. See Appendix C.9.
9. Kermani, N.A. 2021. Volatile and Heat Recovery System – Labotek Case Study. See Appendix C.11.
10. Mattia, A. 2021. Electrification of the Heat Supply through Heat Pumps – Application in the brewery industry. See Appendix C.12.

1.2 Methods

The applied methods are presented in detail the individual reports in the attachment.

We have been working both on the level of the complete industry and the individual sectors, as well as for individual heat pumps. This means that the focus of the projects has been on highly different levels. Even under this constraint the applied methods have been aligned.

The calculations in the analyses have been based on application of mathematical models, by applying the basic laws of thermodynamics - mass balance, energy conversion related to the first law, and respecting the second law in modeling of heat transfer and heat pumping.

The economic analyses have been based on calculations of investment and operating costs of the analyzed systems and determination of business economic parameters as payback period and net present value compared to business as usual scenarios.

The analyses have involved mapping of the present energy use of the system. This requires a significant compilation of process insights and data for having a complete understanding of the energy use. To the extent possible, the calculations have been based on parameter values of high accuracy and certainty. However, estimates and projections based on literature and engineering judgment have been of significant importance in the assessment. To large extent these have been studied based on parameter variations for evaluating the uncertainty of the results.

For best possibly analyzing the options for electrification, it has been a basis for the work to investigate options for energy efficiency improvement of the systems initially. For the case studies this has been based on the application of pinch analysis and process integration. The remaining demands have been analyzed for options for conversion to electric supply.

The models have been implemented in Microsoft Excel and in EES Engineering Equation Solver.

This means that the priority of the solutions has been:

1. Energy efficiency by process integration using heat recovery from excess heat to heat demands: In reality this will result in additional electricity consumption for pumping and it may accordingly be seen as electrification similarly to heat pumps.

2. Heat pumping by use of internal sources: This leads to additional heat recovery from excess heat, which will be regained and lifted in temperature by heat pumps. The heat pumps may be open and use the excess stream directly as the working fluid, or closed vapor compression cycles. The open solutions are usually based on Mechanical Vapor Recompression (MVR).

3. Heat pumping based on external sources: This will provide the lowest COP for the heat pumps, and accordingly has lower priority.

4. Direct electric heating: If there are no options for heat pumping, due to the required temperature levels or that the solutions would be infeasible, electrification may be obtained by heating by use of electricity. Because of the higher price of electricity compared to natural gas, this solution may be less feasible. However, there would usually be options for higher efficiency because of lower loss.

The actual implementation of the results of the work have been applied in the case of the plastic granulate drying for Labotek. In this case the analyses have led to actual demonstration of the results.

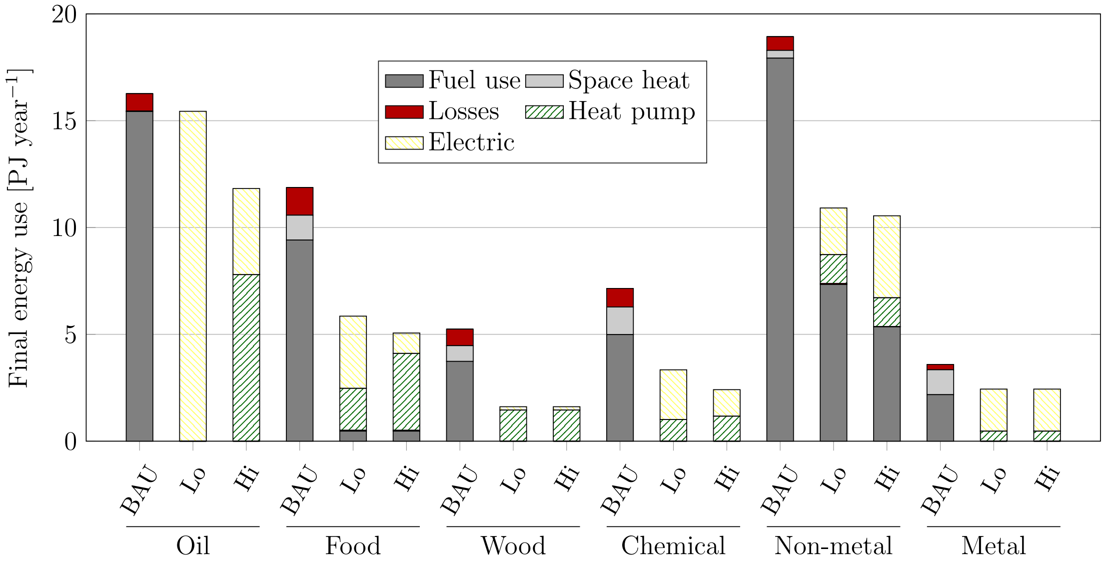


Figure 1.7: Potential for electrification of Danish industry sectors [6]

1.3 Results

1.3.1 Potentials for the electrification of industrial processes in Denmark

The work includes an assessment of the potential for electrification in Danish industry in Appendix A.1 and Appendix A.2. It is based on a mapping of the energy use in Danish industry [19], including process industry. The energy use for process heating in the various branches has been distributed to different processes and types of energy. For 22 industry branches with significant energy use, this has been extended to also include the temperature distribution at different levels of the energy use as well as of the resulting excess heat [4]. In the present work, the model has been extended to include evaluation of the potential for use of electrification by either MVR, heat pumps based on internal excess heat or ambient sources and electric heating. This analysis has led to the results presented in Figure 1.7. It shows significant potential for electrification of the analyzed sectors, i.e., oil and gas, food, wood, chemical, non-metal, and metal, based on two different assumptions of technological levels. In total Danish industry may be converted from 63 PJ use of fossil fuels to using between 5 PJ and 8 PJ gas depending on technology levels. The remaining demand may be electrified to use 34 PJ electricity.

On the other hand, the assessment of bottlenecks for reaching electrification of industry

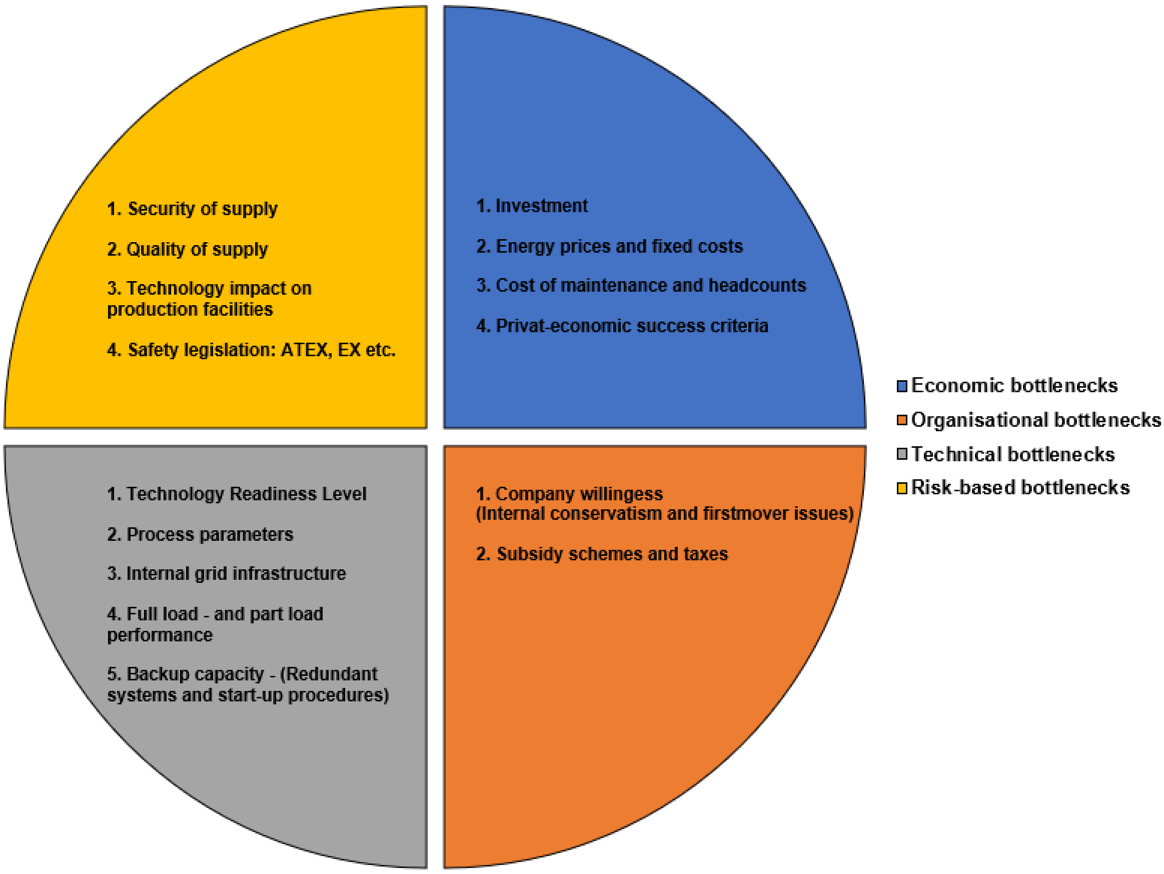


Figure 1.8: Bottlenecks for the electrification of industry A.4

(Appendix A.4 and Appendix A.5) is illustrated in Figure 1.8. The analysis has identified different groups of potential barriers caused by company-specific issues as well as societal issues. For the company-based risks 15 bottlenecks ranging over risk-based, economical, organizational, and technical ones were found. The severity of these is varying and some may be handled rather easily. Others may be important and may result in electrification not being accomplished. Some of the more important bottlenecks are obviously related to high investment and the price of electricity which is significantly higher than for natural gas, also for future projections. But also the technological levels of e.g., high-temperature heat pumps, risks related to security of supply and development in the infrastructure related to extensive expansion of renewable power production are important.

1.3.2 Status and technology for high temperature heat pumps

Reaching the potential for electrification will necessarily require high-temperature heat pumps for industrial use. These need to be proven in actual industrial production for the given demand. Presently, heat pumps are market-ready for use up to about 100 °C, but also above this level solutions exist. These have been mapped (See Appendix B.1 and Appendix B.2) based on a literature survey and further investigation of state-of-the-art. The solutions for high temperature typically have few actual units in operation, but it is clear that several are also gaining a significant number of operating hours or will be demonstrated in projects in the near future. This will surely lead to high temperature heat pumps becoming more attractive for industry and overcome some of the identified bottlenecks. The mapping also identified a number of novel solutions based on innovative technology, which may reach the market in the near future. Only a few Danish innovations were found, while other countries as Norway, Austria and Japan, seem to have a number of initiatives available for the market. Some recent Danish research projects may however lead to new solutions in the coming years.

It is a significant constraint that the COP of a heat pump is dependent on the temperature lift. Accordingly, it is important to identify heat sources at the highest possible temperature for heat pumps, as this will result in the lowest demand for electricity and operating costs.

For higher temperatures above 150 °C, the analysis in Appendix B.3 and Appendix B.4 analyzed possible configurations of heat pumps. One is a cascade heat pump using a hydrocarbon working fluid at the low stage and water (R-718) for reaching high temperature – Figure 1.9. The second solution proposes a gas cycle operating according to the reversed Brayton cycle using supercritical carbon dioxide R-744 as working fluid. The two systems have been compared for cases related to alumina production and spray drying in milk powder production based on technical performance and economy

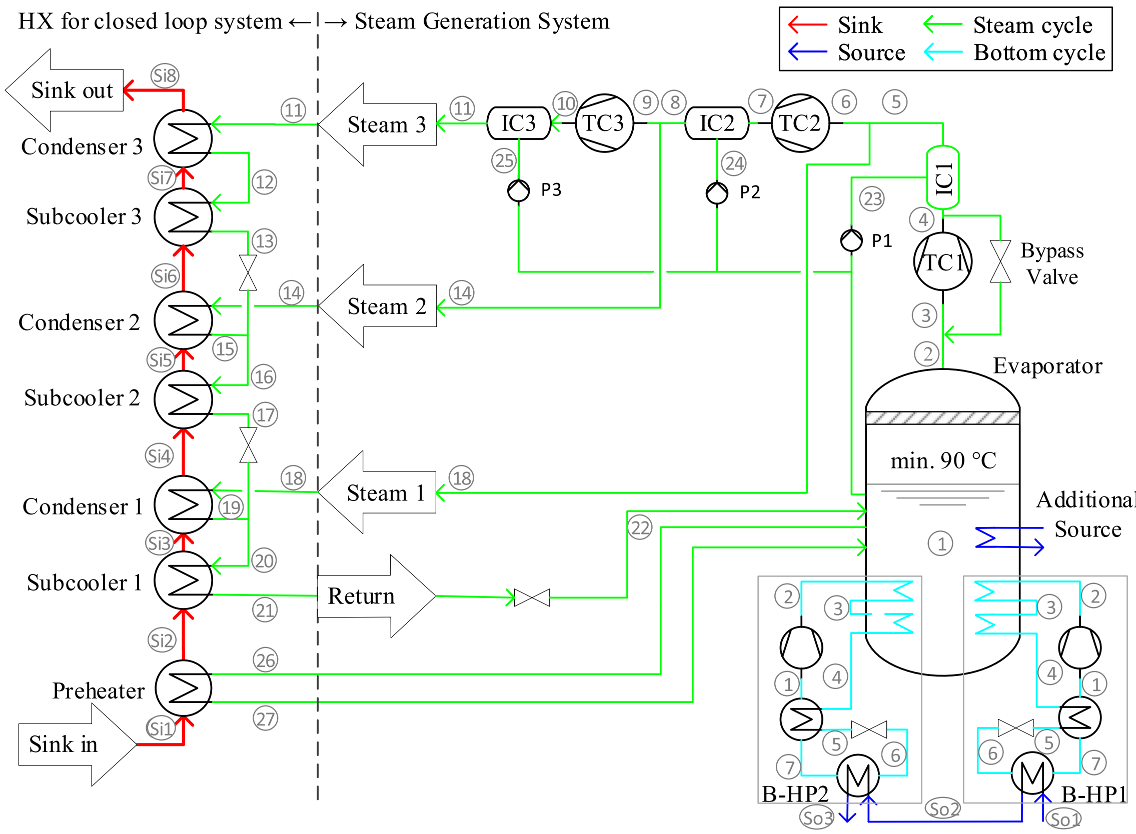


Figure 1.9: Cascade heat pump configuration for high temperature [20]

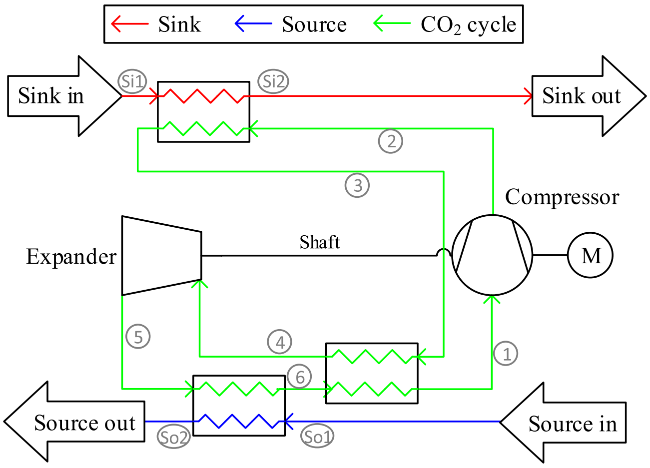


Figure 1.10: Brayton cycle heat pump configuration for high temperature [20]

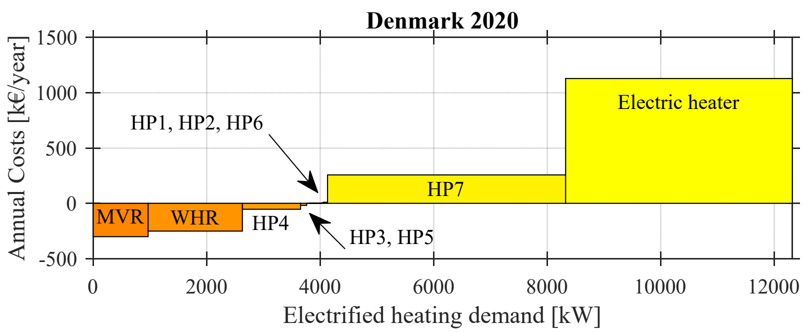


Figure 1.11: Feasibility of investment in electrification for milk powder production [5]

under different conditions. The results show that the operating costs of both systems seem to be attractive, while investment related to retrofit makes them less competitive compared to existing natural gas systems. If tax for CO_2 emission is implemented, the heat pump solutions become significantly more attractive if renewable electricity sources are used.

1.3.3 Industrial case studies

The project has covered the potential for electrification in case studies. All of these indicate a significant potential for electrification of industrial process heating, however, with varying feasibility.

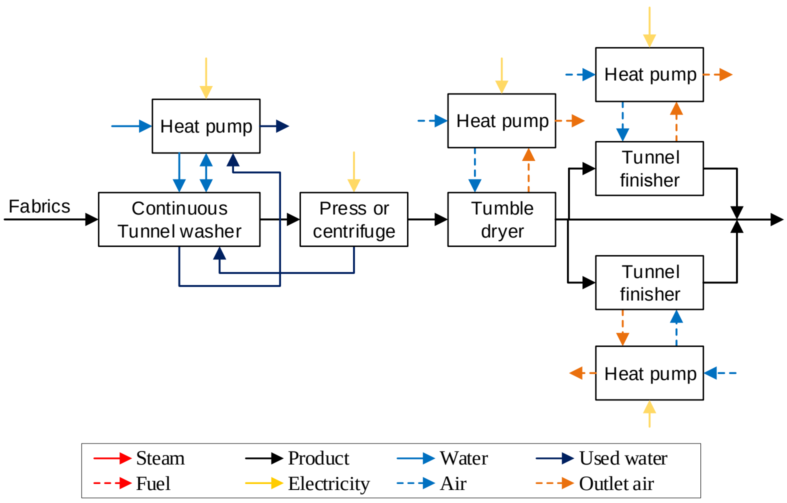


Figure 1.12: Electrified configuration of steam laundry [6]

A comparative assessment of electrification strategies for industrial sites: Case of milk powder production In [5] it was found that a milk powder production facility from a technical viewpoint may be converted to full direct electrification by use of the suggested configurations in Appendix B.3. The results also show the variation of the feasibility of the different parts of the investment as illustrated in figure 1.11, which shows that MVR and heat recovery have the best feasibility over the full lifetime, while heat pump solutions range close to zero and electric heating presently results in net additional cost. Further results are presented in the slides from the webinar in Appendix C.1.

Energy integration and electrification opportunities in industrial laundries For the case of an industrial laundry facility a similar study investigating options for electrification by means of heat pumping and direct heating is covered in [6]. A configuration for electrification using central heat pumps is shown in Figure 1.12. The results included in Appendix C.2 and Appendix C.3 show that for this facility electrification is barely feasible from an economic viewpoint given the current frame conditions for Denmark and Germany.

Electrification of industrial processes with low-to-medium temperature heat demand: CP Kelco case study The case of pectin production was analyzed in [17], which covered a thorough mapping and analysis of the complete facility of CP Kelco. It was found that energy use may be used by between 33 % and 69 % by electrification. In

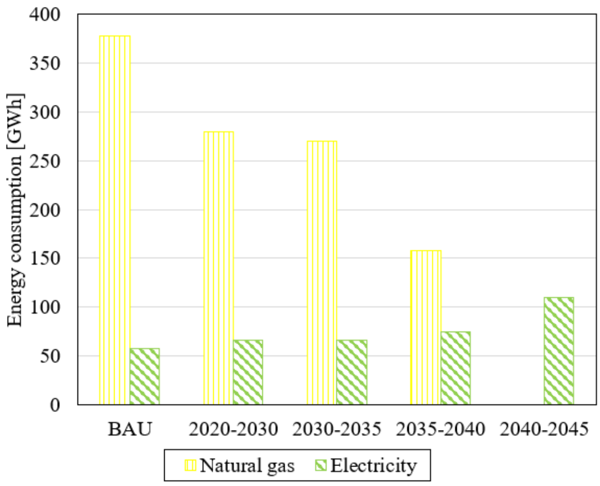


Figure 1.13: Electrification development for CP Kelco [17]

addition the work included a detailed plan for electrifying the production over the coming decade. The results of the study are presented in Appendix C.4 and Appendix C.5.

Energy optimization and electrification of a brewery In the master thesis by Andreas Helk [11], the potential for energy optimization and electrification of process heating at Harboe Bryggeri was assessed. Also for this process it was determined that the process may be fully electrified using heat pumps and electric heating. The mapping showed that electricity already covers a significant share of the energy use at the facility. This use would be continued and extended by electrification. The existing use of fuels for heating may for some conditions be converted to using electricity but only needing 1/3 of the current demand.

In addition, the project presented a procedure for covering both energy efficiency and electrification of a facility. Crucial parts of this procedure involve the energy mapping and process integration analysis.

The results of the case study are presented in Appendix C.6 and Appendix C.7.

Electrification of CP Kelco steam supply For the high-temperature processes at CP Kelco the study presented in Appendix C.8 and Appendix C.9 focused on the electrification of the steam demand for drying and extraction processes which will remain after installing heat pumps to the feasible extent. The remaining demand will be about 11 % of the present one. This may be converted by electric heaters provided by SAN

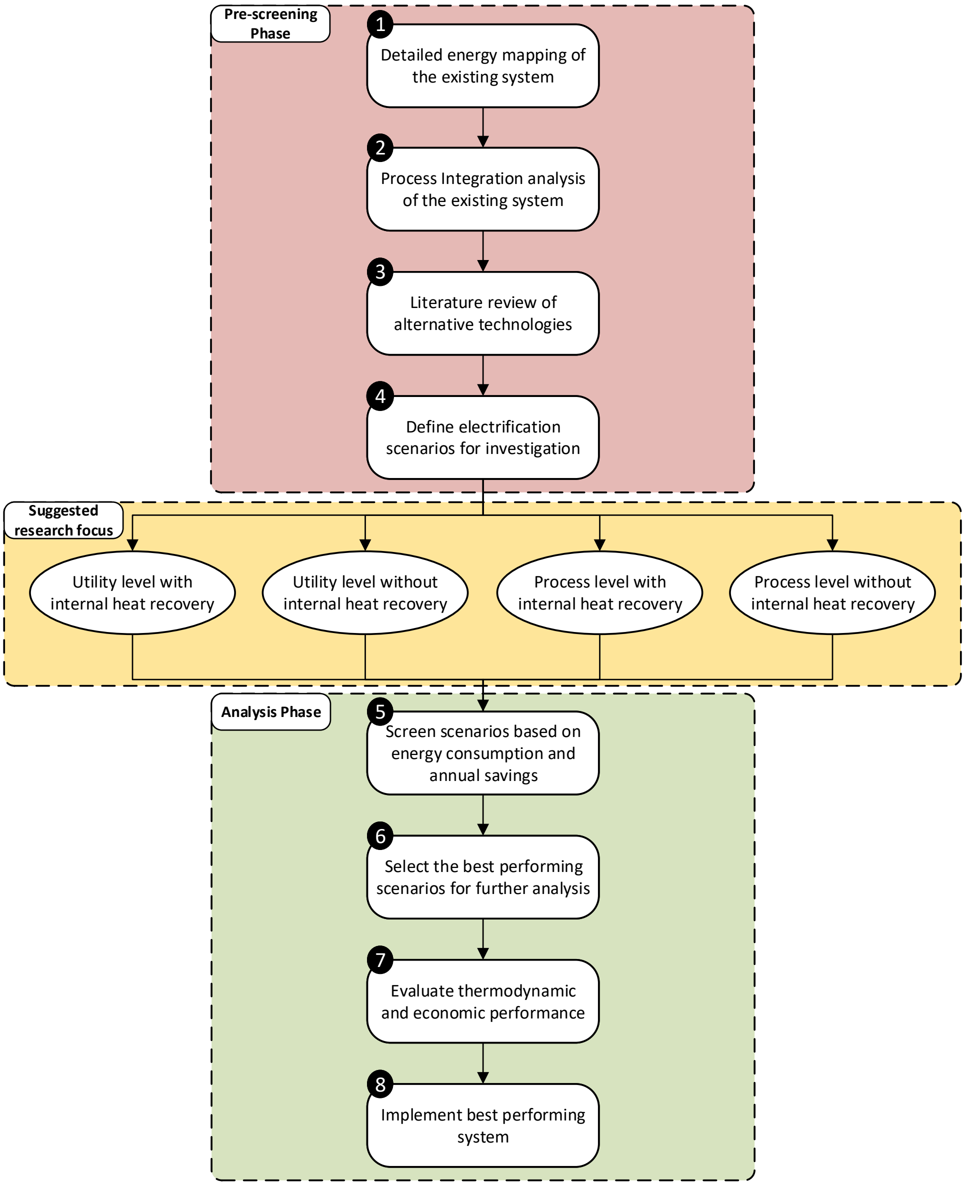


Figure 1.14: Procedure for energy efficiency and electrification of an industrial facility [11]

Figure 1.15: Labotek heat recovery unit installed in a production facility

Electro Heat. A significant additional reduction of the demand related to this would appear because decreased losses in the heating system. Economically, the transition would not be fully feasible given the present frame conditions.

Volatile and Heat Recovery System Design - Labotek Case Study Labotek is a manufacturer of equipment for the plastic industry. In the present work, the drying of plastic granulate before molding was analyzed with focus on conversion of electric heating to increased heat recovery and heat pump use. The case study involved analysis of the potential for heat recovery from the air after drying and use of heat pumps for additional heat integration. The analysis showed that by heat integration it would be possible to have 73 % energy recovery. By additionally integrating heat pumping, more than 100 % of the excess heat could be recovered including the heat pump power. The results have led to the development of a heat-integrated unit which is already on the market and has been installed, e.g., at an Egyptian facility as shown in Figure 1.15. Further details about the results are presented in Appendix C.10 and Appendix C.11.

Integration of high temperature heat pumps in brewing processes The work in the thesis [15] was focused on high-temperature heat pumps in breweries. A significant part of the investigation was connected to the mapping of the demand in the process, because of the combination of continuous and batch processes. The potential for process integration was closely related to this and energy storage might be part of the solution. It was determined that high-temperature heat pumps of 469 kW power and MVR of 19 kW power would be beneficial for the process. The work is presented in Appendix C.12.

Integration and optimization of a reversed Brayton cycle coupled with renewables and thermal storage in an oil refinery The thesis by [14] was aimed at electrification in oil refining. This requires very high temperatures of up to 400 °C, and is a quite demanding case for heat pumps. The case was analyzed based on reverse Brayton cycle heat pump solutions. It was found that the heat pumps would reach COPs on the order of 1.5, which is a result of the temperature demands. From an economic viewpoint this case was not fully feasible. However, the presented solutions are not far from the costs related to fuel-based solutions and under some conditions, they may be competitive.

1.4 Discussion

The presented results show a significant potential for electrification of both the Danish industry and its sectors as well as for the cases analyzed for individual production plants. It should be kept in mind that the results are based on modeling and have applied estimates of parameters. This does mean that the actual potential may not be exact, in particular related to economics, which may be impacted significantly by future development and regulation. As an example, it may likely be the case that emission of greenhouse gases will have a tax in the future. This will cause the cases where fossil fuel remained economically feasible to tend towards solutions without emissions.

An important assumption in this respect is that electricity in the near future will be produced without greenhouse gas emission – based on renewable and sustainable sources. Presently, electricity production in Denmark involves CO_2 emission, which means that a tax on emission would not necessarily benefit electrification today. The development of the infrastructure for the electricity grid and expansion of renewable power production is not part of the present work but will accordingly be required for the transition based on electrification.

Some processes will not be possible to electrify directly by use of heat pumps or electric heating. For these, indirect electrification by use of fuels produced by power-to-X may be applied. However, this approach will not be beneficial if direct electrification is possible, due to significantly lower efficiency compared to heat pump solutions.

For the realization of electrifying the process industry, further development of heat pumps is paramount. Several innovative solutions are on the market, and several projects investigate the options and demands for future development. It is, however, needed to have feasible heat pump equipment available for the electrification to actually take place. There seems to be missing a clear view of the demands with respect to e.g., capacity, temperature glides, temperature lifts and refrigerants. This makes the requirement less clear and perhaps a highly diverse market is defining the actual demand. This obviously complicates matters for the suppliers.

Obviously, the highest possible COP should be targeted for efficiency and economy reasons. This will mean that the required temperature lifts should be as low as possible, and that the demand for comprehensive mappings of energy flows in the facilities and hence the potential low-temperature sources for heat pumps should be identified carefully.

1.5 Conclusion

The analyses in the project have covered the potential for direct electrification of process heating in Danish industry. Direct electrification covers the following options ordered according to the estimated performance in terms of COP – mechanical vapor recompression, heat pumps using internal or external low temperature sources and electric heating. The COP is not directly a measure of *efficiency* in terms of how well the unit performs in relation to the theoretical potential. Efficiency also relates to the temperature lift and is measured by comparison the theoretically ideal limit, the Carnot cycle – or more generally the Lorenz cycle. In terms of economic performance compared to operating costs COP is a useful measure, because it determines the heat produced compared to the electricity consumption. This can be compared directly to the cost of using fossil fuel.

The potential for electrification of the industry on an overall level and on sector levels was analyzed and showed that the process heating demand in the industry may be converted from 63 PJ fossil fuels to direct electric heating, such that only between 5 PJ and 8 PJ fuels are needed. The transition involves energy efficiency by use of heat pumping, which means that the energy demands will be reduced to between 34 PJ and 40 PJ. Electrification will result in reduced CO_2 emissions, but it is also required that the electricity system is converted to renewable sources for reaching the climate targets.

The results include a mapping of the bottlenecks related to electrification of industry. A number of bottlenecks have been identified and involve issues covering techno-economic parameters related to the operation, but also organizational topics and demands for the development of the infrastructure.

A mapping of state-of-the-art of industrial heat pumps, focusing on high temperature solutions shows that a number of options are available for varying temperature demands and capacity and at different levels of technology readiness. The development of high-temperature solutions will be needed for reaching the potential for electrification.

The project covers a number of case studies for industrial facilities. This includes pectin production, milk powder, brewing, industrial laundry, plastic drying, and a case for high temperature demand for oil refineries. The cases have been analyzed based on a procedure developed and applied throughout the projects. It has involved detailed mapping on the present production, options for energy efficiency and heat integration and energy and economy performance of electrification solutions. It was shown that from a technical viewpoint full electrification may be obtained for several of the plants. Full electrification will involve MVR, heat pumping and direct electric heating. This also means that varying economic feasibility was found for the solutions, which may be implemented individually. In particular this was used for the pectin case which also involved a detailed planning of the electrification process of the facility.

1.6 Bibliography

[1] Herbert Bechem, Markus Blesl, Marc Brunner, Jochen Conrad, Tobias Falke, Clemens Felsmann, Martin Geipel, Norman Gerhardt, Wolfgang Glaunsinger, Johannes Hilpert, Alois Kessler, Martin Kleimaier, Silke Köhler, Rolf-Michael Lüking, Philip Mayrhofer, Andrea Meinzenbach, Elmar Metten, Helene Neugebauer, Dieter Oesterwind, Christoph Pels-Leusden, Joachim Plate, Arno Pöhlmann, Philipp Riegebauer, Jörg Rummeni, Peter Schegner, Armin Schnettler, Stefan Tenbohlen, Serafin von Roon, and Jens Werner Bernhard Wille-Haussmann. Potenziale für strom im wärmemarkt bis 2050. Technical report, VDE Verband der Elektrotechnik, 2015. URL `http://www.energiedialog2050.de/BASE/DOWNLOADS/VDE_ST_ETG_Warmemarkt_RZ-web.pdf`.

[2] Fabian Bühler. *Energy efficiency in the industry: A study of the methods, potentials and interactions with the energy system*. PhD thesis, DTU Technical University of Denmark, 2018. URL `https://orbit.dtu.dk/en/publications/energy-efficiency-in-the-industry-a-study-of-the-methods-potentia`.

[3] Fabian Bühler, Tuong-Van Nguyen, and Brian Elmegaard. Energy and exergy analyses of the danish industry sector. *Applied Energy*, 184:1447–1459, 2016. ISSN 0306-2619. doi: 10.1016/j.apenergy.2016.02.072.

[4] Fabian Bühler, Stefan Petrovic, Torben Schmidt Ommen, Fridolin Müller Holm, and Brian Elmegaard. Identification of excess heat utilisation potential using GIS: Analysis of case studies for Denmark. In *Proceedings of ECOS 2017: 30th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, 2017. URL `http://www.ecosconference.org/`.

[5] Fabian Bühler, Benjamin Zühlsdorf, Tuong-Van Nguyen, and Brian Elmegaard. A comparative assessment of electrification strategies for industrial sites: Case of

milk powder production. *Applied Energy*, 250:1383–1401, 2019. ISSN 0306-2619. doi: 10.1016/j.apenergy.2019.05.071.

[6] Fabian Bühler, Fridolin Müller Holm, Benjamin Zühlsdorf, and Brian Elmegaard. Energy integration and electrification opportunities in industrial laundries. In *Proceedings of ECOS 2020: 33rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, 2020. URL https://ecos2020.org/.

[7] Danish Energy Agency. Energy policy toolkit on energy efficiency in industries – experiences from denmark. Technical report, Danish Energy Agency, 2015. URL https://ens.dk/sites/ens.dk/files/Globalcooperation/ee_in_industries_toolkit.pdf.

[8] Statistics Denmark. Ene2ha: Energy account in common units (detailed table) by use and type of energy. Online, 2015. URL https://www.statbank.dk/ENE2HA.

[9] Energistyrelsen. Energistatistik 2019. Technical report, Energistyrelsen, 2020. URL https://ens.dk/sites/ens.dk/files/Statistik/energistatistik2019_dk-webtilg.pdf.

[10] EURELECTRIC. The benefits of electrification: Electricity's contribution to sustainable energy use. Technical report, EURELECTRIC, 2015. URL https://www.eurelectric.org/media/1964/electrification_report_final-2015-030-0437-01-e.pdf.

[11] Andreas Helk. Energy optimization and electrification of brewery, energioptimering og elektrificering af bryggeri. Master's thesis, Technical University of Denmark, 2020.

[12] Sebastiaan Hers, Maarten Afman, Sofia Cherif, and Frans Rooijers. Potential for power-to-heat in the netherlands. Technical report, CE Delft, 2015. URL https://www.cedelft.eu/en/publications/1730/potential-for-power-to-heat-in-the-netherlands.

[13] IEA. World energy balances: Overview. Technical report, International Energy Agency, 2020. URL https://www.iea.org/reports/world-energy-balances-overview.

[14] Vergis Kousidis. Analysis and optimization of high-temperature heat pumps in combination with renewable electricity sources, analyse og optimering af højtem-

peraturvarmepumper i kombination med vedvarende energikilder. Master's thesis, Technical University of Denmark, 2019.

[15] Alessandro Mattia. Integration of high temperature heat pumps in brewing processes, integration af højtemperaturvarmepumper i bryggeri. Master's thesis, Technical University of Denmark, 2020.

[16] Fons Pennartz. An all-electric sustainable slaughterhouse, relying on heat pumps for its heat. *Dutch Heat Pumping Technologies Journal*, (2):15–16, 2017. URL https://hpc2017.org/wp-content/uploads/2017/06/DHPTJournal-Industrial-applications-Online-medium.pdf.

[17] Morten Sandstrøm Petersen and Niklas Bagge Mogensen. Elektrificering af industrielle processer med lav- til mellemtemperaturbehov: Casestudie af pektinproduktion, electrification of industrial processes with low-to-medium temperature heat demand: Case study of pectin production. Master's thesis, Technical University of Denmark, 2019.

[18] Jean Schweitzer, Lars Jørgensen, Jan de Wit, and Negar Sadegh. Danish natural gas utilisation today: Mapping of the danish natural gas utilisation and evolution. Technical report, FutureGas, 2019. URL https://futuregas.dk/wp-content/uploads/2019/11/FG_WP2-Task-1-Mapping-of-the-Gas-utilisation-in-DK-V14.pdf.

[19] Louise Hedelund Sørensen, Peter Maagøe Petersen, Søren Draborg, Christensen, Kurt Mortensen, and Jørgen Pedersen. Kortlægning af energiforbrug i virksomheder. Technical report, Energistyrelsen, 2015. URL https://ens.dk/sites/ens.dk/files/Energibesparelser/kortlaegning_af_energiforbrug_i_virksomheder.pdf.

[20] B. Zühlsdorf, F. Bühler, M. Bantle, and B. Elmegaard. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C. *Energy Conversion and Management: X*, 2, 2019. ISSN 2590-1745. doi: 10.1016/j.ecmx.2019.100011.

A Potentials for the electrification of industrial processes in Denmark

Potentials for the electrification of industrial processes in Denmark

Fabian Bühler[a], Fridolin Müller Holm[b] and Brian Elmegaard[c]

[a] *Technical University of Denmark, Kgs. Lyngby, Denmark, fabuhl@mek.dtu.dk*
[b] *Viegand Maagøe A/S, Copenhagen, Denmark, fmh@vmas.dk*
[c] *Technical University of Denmark, Kgs. Lyngby, Denmark, be@mek.dtu.dk*

Abstract:
The energy supply of processes in the industry and many service sectors relies heavily on the combustion of fossil fuels, which are either used directly to supply heat or indirectly through utility systems. While the share of renewable energies in the electricity mix in Europe is increasing, the industry sector has primarily focused on energy efficiency. With the industrial reliance on fossil fuels, the needed decarbonisation can only take place when replacing fossil fuels with renewable energy sources. This change is however difficult for many industries, as they require high temperature process heat, thermal energy at high rates and short payback times for investments.
By converting the energy supply of industries to a fully electric one, it is possible to considerably reduce CO_2-emissions in a future fossil fuel-free power system. The key to this transformation are technologies which allow the efficient use of electric power for process energy supply. By using heat pumps on a large scale for example, a reduction in primary energy use is possible.
In this work electrification options and pathways for the industry sector are described and their implementation potential was assessed. The work considers the most recent publications describing electrification technologies, methods and potentials. For the case of Denmark, an analysis of the industry sector is performed to show the potential and requirements of an all-electric industry. The top-down approach for the sector analysis was complemented with economic considerations.
The results give a framework for possible CO_2-emission savings and requirements towards energy costs, to drive the industry towards electrification.

Keywords:
Electrification, Decarbonisation, Industry, Heat pump.

1. Introduction

The Paris Agreement [1] aims to restrict the increase in the average global temperature to below 2 °C above the pre-industrial level and to pursue efforts to limit it to 1.5 °C. Reaching these goals requires the energy sector to have net-zero CO_2-emissions by 2060 and 2040 respectively [2]. While the power sector changes from fossil fuels to renewable energy sources, the building sector reduces emissions by improved insulation, solar energy and heat pumps, a focus is often placed on challenges in the transport sector. Efficiency and electrification are set as targets to reach the net-zero emissions for many forms of transport, while aviation and long-haul freight remain uncertain [2]. The decarbonisation of the industry sector is however often overseen, despite the industry accounting for 21 % of the direct global greenhouse gas emissions in 2010 [3].

The industry sector has focused on energy efficiency over the last decades, but also with the implementation of best available technologies, the energy intensity of the sector could only be reduced by 15 % to 30 % [3, 4]. A large fraction of the greenhouse gas emissions in the industry originates from the combustion of fossil fuels or is process-related (e.g. calcination). A decarbonisation of the industry can happen on a large scale with three main technology options, namely replacing fossil fuels with bioenergy, electrification of processes and the implementation of carbon capture and storage [5].

The total final energy use for heat in the industry worldwide was 79 EJ in 2011 [6], which was around three-quarters of the total industrial energy demand [2]. In 2015, 55 % of the final energy use of the industry in the EU was covered by fossil fuels and 31 % by electricity. A large fraction of the fossil fuel is combusted to supply process heat directly or indirectly through steam boilers. Depending on the industry and process, the heat is required at different temperature levels. Low-temperature heat ($< 100\,^{\circ}C$) is primarily used in the food industry, while high temperature heat ($> 500\,^{\circ}C$) is requried in the production of steel, cement and glass [7]. The provision of this process heat, with other sources than the combustion of fossil fuels is required to obtain a full de-carbonisation of the industry sector. Supplying process heat with electric technologies can present challenges and opportunities, which depend highly on the industry sector and process characteristics. Electrification reduces energy-related CO_2-emissions, but can also allow for a reduction in final energy use through e.g. heat pumps (HP) and have social and economic benefits, such as a reduction in local air pollution, lower water demand, increased productivity, flexibility and controllability of processes [8]. The technical challenges with electrifying industrial processes depend largely on the processes themselves and the temperature requirements. The choice of Power-to-Heat technologies largely depends on process and temperature requirements. Some promising electrification technologies, such as high temperature heat pumps (HTHP) or heat pump-assisted distillation, have a low technology readiness level [9], while other available technologies, such as electric boilers and Mechanical Vapour Recompression (MVR), are infeasible under current economic conditions. Some industrial processes require further fuels as a feedstock or their process characteristics make the fuel substitution impossible.

It is however evident that electrification will play an important role in reducing the industrial CO_2-emissions and that more electric technologies will become economically feasible with technological advancements and adjustments in energy prices. The analysis of electrification technologies, establishment of industrial electrification potentials, development of pathways and strategies for the electrification of industrial sites and sectors is thus an important contribution to accelerating the industries shift to a fossil-free production.

The overall aim of this paper is to contribute to the development of electrification options and pathways for the industry sector. This is achieved by (i) describing electrification options and technologies, (ii) by analysing the industry sector to show the potential and requirements of an all-electric industry using a top-down approach and (iii) assess economic boundary conditions for electrification.The article is structured as follows. First some considerations for the electrification of the industry are presented, together with a review of the literature (Section 2.. This is followed by a description of the data and method for the establishment of the electrification potential in Denmark (Section 3.). The results in terms of electrification technologies and potentials are presented in Section 4..

2. Electrification in the industry

Besides the reduction of CO_2-emissions and thereby contributing to the targets set for global warming, the increased use of renewable electricity has a number of other benefits for the industry. Many electric heating technologies are more efficient than fuel-fired systems, reducing the energy required for a given process. In many cases electric heating is also faster and more precise, increasing productivity and quality [10]. These benefits in combination with converging energy prices for fossil fuels and renewable electricity, gives industries strong economic incentives to consider electrifying their processes. As many electric systems can be installed modularly, varied in size and operated besides traditional heating systems, their implementation can occur gradually and thereby distribute costs and risk over time [10].
Electrification can be defined as the adoption of electricity-based technologies that replace technologies currently fueled by nonelectric sources, typically fossil fuels [8]. In the industry the majority of thermal heating processes are supplied by non-electric sources, directly through the heat of combustion or indirectly through steam or hot water from boilers. These processes are very diverse and possible electric-technologies require further analyses.
In this Section, first options and technologies for electrifying an industrial site are given. This is followed by a summary on research establishing electrification potentials.

2.1. Industrial electrification options

Strategies and methods for the electrification of industrial sites have not yet been studied in detail. The approach for electrifying an industrial site is however crucial to guarantee an efficient conversion. When electrifying an industry it is thus important to consider, opportunities for energy savings, possibility to reduce the final process energy demand through electrification technologies, evaluate process alternatives and opportunities for flexibility and production increase.
Wiertzema et al. [11] presented a bottom-up methodology for assessing electrification options for industrial processes. The authors highlight the importance to consider systemic effects when electrifying processes, as processes and unit operations are highly interconnected. The proposed method is based on process integration studies and starts by a description of the system and the selection of possible electrification technologies. Based on the technology choice, a process integration study is performed with modified unit operations, which are consequently modelled, simulated and assessed. Based on the assessment several iterations with different technologies are required.

den Ouden et al. [9] described two electrification strategies, namely flexible electrification in which electric technologies are used when prices are low and baseload electrification. It is further highlighted that electrification can forego in the utilities or in the core process and primary process streams. The choice of electrification technology thus depends on the strategy and application area.
The electrification of an industrial site can take place on the following levels:

1. Fuel: Replacement of the fuel used to generate process heat with electro-fuels from renewable sources, such as hydrogen.

2. Utility: Replacement of a central fossil fuel-fired boiler with e.g. electric boiler or a central heat pump.

3. Process: Replacing the process energy supply with an electric technology, e.g. heat pump, resistance or infrared (IR) heating, while keeping the process operation identical.

4. Unit operation: Replacement of the current unit operation with a fully electric one, e.g. mechanical separation instead of evaporation.

While an electrification of the fuel supply or utility level has the least impact on production processes, they will often not generate reductions in energy use nor improvements in production throughput and product quality. Electromagnetic heating technologies, such as IR, radio frequency (RF) and microwave, have a great potentials for many applications [10].

2.2. Electrification potential

The analysis and quantification of electrification potentials in the industry is of great importance. Based on such analyses, promising industries can be identified, requirements for structural changes can be established and the need for technological development and support can be analysed.
Gruber et al. [13] analysed the potential for Power-to-Heat in industrial processes in Germany and the opportunities for flexibility in the energy use of the electric technologies. The study found that there is an electrification potential of around 648 PJ per year and allows for a reduction in final energy use between 6 % and 13 %. Approximately 792 PJ of the final energy use for process heating cannot to be electrified, as fuels are required as feedstock (e.g. coke making) or a complete production change would be necessary (e.g. steel production in blast furnaces) which makes a complete electrification impractical.
For the Netherlands, the Power-to-Heat potential was estimated in different sectors [15]. The report assumed that only heat demands up to 260 °C can be electrified, which leads to a conservative electrification potential of 133 PJ in 2012 and an expected 128 PJ in 2020. This corresponds to 33 % of the total industrial heat demand. The main opportunities for electrification are found in the food and beverage industry, chemical and paper industry.
Mai et al. [8, 16] analysed scenarios of electric technology adoption in the United States for different sectors. With respect to industrial process heating, an almost full electrification by 2050 was assumed in the high electrification scenario [8]. It was assumed that conventional boilers could be replaced by electric boilers and industrial heat pumps used in the food, pulp

and paper, and chemical industry. Induction heating, electrolytic reduction, resistance heating and melting were assumed to electrify other sectors such as glass, metal fabrication and non-ferrous metal. Solely in the iron and steel industry, a share of 79 % of process heat remained non-electric. The authors highlight however that electrification potentials in the industry are more challenging to assess and that more detailed research is needed to evaluate electric technologies for high temperature and large energy process heat demands. When considering the technology adoption rates, which include cost-benefits of the electric technologies, lower levels of electrification are obtained until 2050 [16]. Even in the high electrification scenario, which includes a favourable set of conditions for electrification (e.g. technology breakthroughs, policy support, and underlying societal and behavioural shifts), electric boilers and industrial heat pumps are only marginally adopted. However in drying and curing processes a higher electrification through infrared and ultraviolet heating are obtained. This low level of overall industrial electrification is a result of linking industrial electrification with productivity benefits and, this may lead to conservative adoption assumptions for certain electrotechnologies.
For Denmark the replacement of natural gas with electricity was investigated for the industry sector [17]. The analysis showed that 88 % of the natural gas use could be substituted with electricity. Only process heat supplied directly through the combustion of natural gas was assessed to be not fully convertible. For these types of processes it was found that 25 % of natural gas use in high temperature processes and 50 % in low temperature processes could be converted.

3. Material and methods

3.1. Energy use in the Danish Industry

The energy supply of the Danish Industry is largely based on fossil fuels. In 2016 the industry accounted for 126 PJ of the total Danish final energy use of 626 PJ [18]. The manufacturing industry represented almost 70 % of the industrial energy use and had a fossil fuel use of 70 PJ. The manufacturing industry in Denmark is characterised by non-energy intensive industries such as the food, beverage, chemical and pharmaceutical sectors. The processing of non-metallic minerals and oil refineries present a further high share of the energy use, but industries in the basic chemical, iron and steel and pulp and paper industry are negligible. The share of renewable energy in the Danish electricity mix was 63.7 % in 2017, with wind energy representing a total share of 43.2 % and biomass 16.6 % [19]. An electrification of fossil fuel-based industrial processes, would thus reduce energy related CO_2-emissions.
As shown in Section 2.2., the electrification potential of industries was established for different countries with a varying level of detail and assumptions. For Denmark an overall assessment for the conversion of natural gas to electricity was done [17]. There remains however the need for a more detailed analysis of the manufacturing industry.
The energy use by temperature level in the main sectors of the manufacturing industry is shown in Figure 1 and by thermal process operations in Figure 2. The numbers are based on the energy use in 2012 of the 22 largest industrial sub-secotrs, which were grouped into six industrial sectors [20, 21]. The energy use for thermal process heating is dominated by temperature requirements between 60 °C and 120 °C in the food, chemical and wood processing industry. This temperature band is characterised by process heating, drying and evaporation. High temper-

ature heat above 500 °C is used in the production of building material and metal processing. The dominating unit operations are heating, baking, sintering, melting and founding.

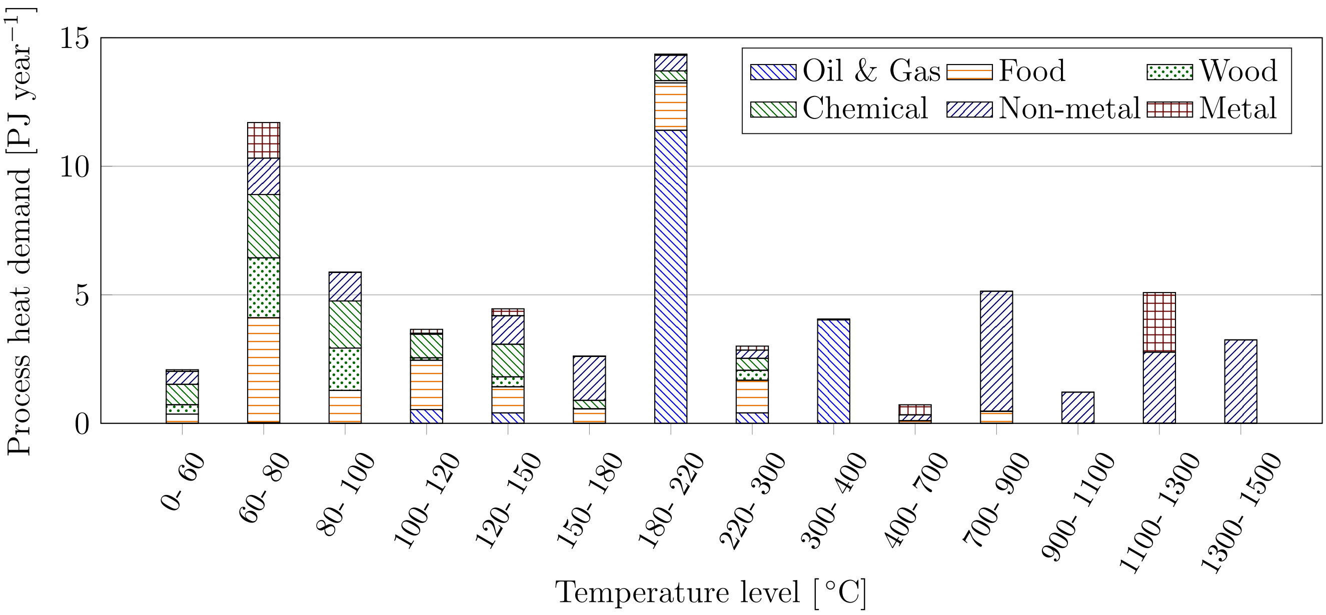


Figure 1: Industrial process heat demand by temperature level and sector in 2012. Based on data from [20, 21]

3.2. Determination of electrification potential

The electrification potential for the Danish manufacturing industry was established following the overall approach by Gruber et al. [13]. Based on the distribution of the heat demand amongst industries, processes and temperature levels, the electrification potential was established using suitable technologies established in Section 4.1. and cases from the literature. For the electrification of a given process different alternatives can be available as described in Section 2.1., depending on the situation at the production site. Additionally, some technologies may not be fully commercial yet or are based on a modification of the core process. Two scenarios were therefore investigated to account for these variations. A first scenario (Lo) considers established technologies and a low willingness to change the core processes. The second scenario (Hi) considers a high degree of technology availability and adoption. Both scenarios were compared to a business as usual (BAU) scenario.

As a large share of the process heat demand in Denmark is at low temperatures, heat pumps are expected to play an important role in the electrification. The COP of the heat pump is determined by the source temperature and type, which varies between industries and sites. It was assumed that heating demands up to 80 °C can be covered by ambient sources at 10 °C. Heat demands above were assumed to have a heat source with a gradual temperature increase up to 80 °C. Previous studies [22, 23] have shown that the majority of excess heat in the industry is available at temperatures below 100 °C. In the absence of sufficient excess heat, other heat sources (e.g. solar or district heating) could be utilised. The COP of the heat pump was

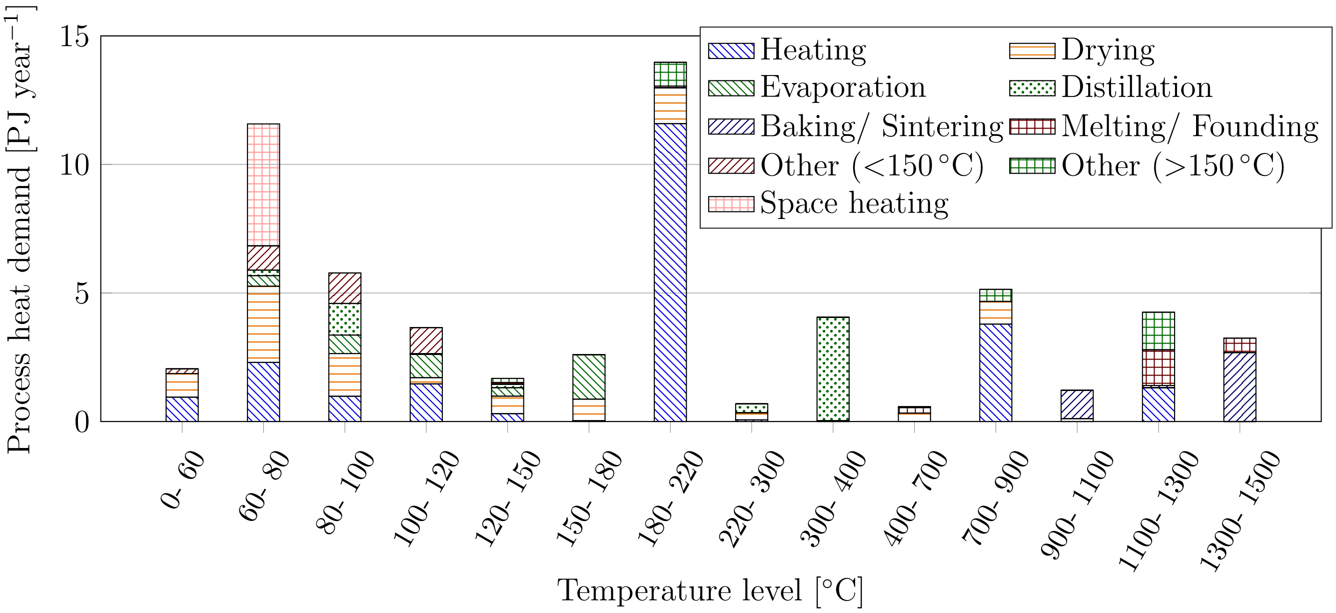


Figure 2: Industrial process heat demand by temperature level and process in 2012. Based on data from [20, 21]

found using the Lorenz efficiency, with an efficiency of 45 %. The required temperature lift was always from the lower to the higher temperature of the temperature band shown in Figure 1 and 2.
The CO_2-emissions of the industry were found using the emissions factors of the fuels [24] used in the industry sector. For electricity the current emission factor in Denmark and the one expected for 2025 were used [25].

3.2.1. Low technological development scenario (Lo)

This scenario takes origin in technologies with a high technological availability. Heat pumps (incl. MVR) were assumed to be able to supply process heat for heating and drying purposes up to 150 °C. Other heating demands supplied through steam or hot air were covered by electric boilers or electric heaters with an assumed efficiency of 100 %. Technologies such as microwave ovens were assumed to be unavailable.

3.2.2. High technological development scenario (Hi)

This scenario assumes that process alternatives can be developed for all processes which require thermal energy. In addition to the previous scenario it was assumed that HTHP can supply process heat up to 400 °C, in the form of steam, air and thermal oil. Using the MVR for evaporation and heat pump distillation was a possibility in all cases.
Based on literature case studies [10] electric-options for other process heating demands were used. This included for example microwave technology to substitute 50 % of energy use in kilns and furnaces. IR drying of materials, reducing energy use by 45 %. Also in the cement production electric heating was possible for parts of the production and increased efficiency by 12 % [26].

4. Results

4.1. Electrification technologies

There are many technologies available to electrify an industrial site or process on the levels presented in Section 2.1.. Electrical heating technologies were presented and discussed in several publications [9, 10, 12–14]. Electric technologies for some industrial processes cannot be identified easily as fuels are used as feedstock or are part of chemical reactions, such as in the steel, cement, petrochemicals and fertilisers production [5]. Table 1 presents a summary of possible electricity-based technologies which can provide energy services for different processes. The technological availability of these technologies is further assessed and technologies which have the potential to increase the production output are marked. Process heat distributed

Table 1: Overview of electrification technologies for different industrial processes and their technological availability and opportunity for increasing production output. The table is based on [9, 10, 12–14]

Process	**Technology**	**Availability**	**Output**
Process heat (steam, water)	Heat pump	High	
	HTHP	Medium	
	Electric boiler	High	
	Electrode Boiler	High	
	Vapour recompression	High	
-Drying	Electromagnetic	Medium	+
	Impulse drying	Low	
	Impingement drying	Low	
-Sterilisation/ pasteurisation	Electromagnetic	Medium	+
	High pressure sterilisation	Low	
-Distillation/ separation	Filtration	Medium	
	Electrical field/ electrostatic	Low	
	Mechanical techniques	Medium	
Baking/ melting/ casting	Induction furnace	High	+
	Electromagnetic	Medium	+
	Direct/ indirect resistance	High	+
	Electric arc furnace	High	
	Plasma heating	Medium	
	Electron beam heating	Medium	+

through water and steam systems has a relatively high technological availability for electrification. For specific unit operations, such as drying and distillation, several additional technologies are available. Their technological availability is however lower, as they often require process modifications.

4.2. Technical electrification potential

The potential for electrification in the Danish industry was found to be high, as shown in Figure 3 for the different industry sectors. Except in the building industry and a small share of the food industry, it would be possible to electrify the energy use for thermal processes. The losses from the fuel conversion in boilers can be almost fully avoided and, through the use of e.g. heat pumps, the final energy use can be considerably reduced. In most sectors the difference in final energy use between the low and high technology development scenario is relatively small, as the heat pumps above 150 °C were assumed to operate at low COP values. In the oil & gas sector changes are more notable as there is a large heating demand between 180 °C and 220 °C, where the heat pump in the high scenario has a COP of 1.5. The distillation of crude oil was in both scenarios assumed to take place with electric heaters, however in the future heat pump or membrane-assisted distillation could become available [11]. For the industry sector as a

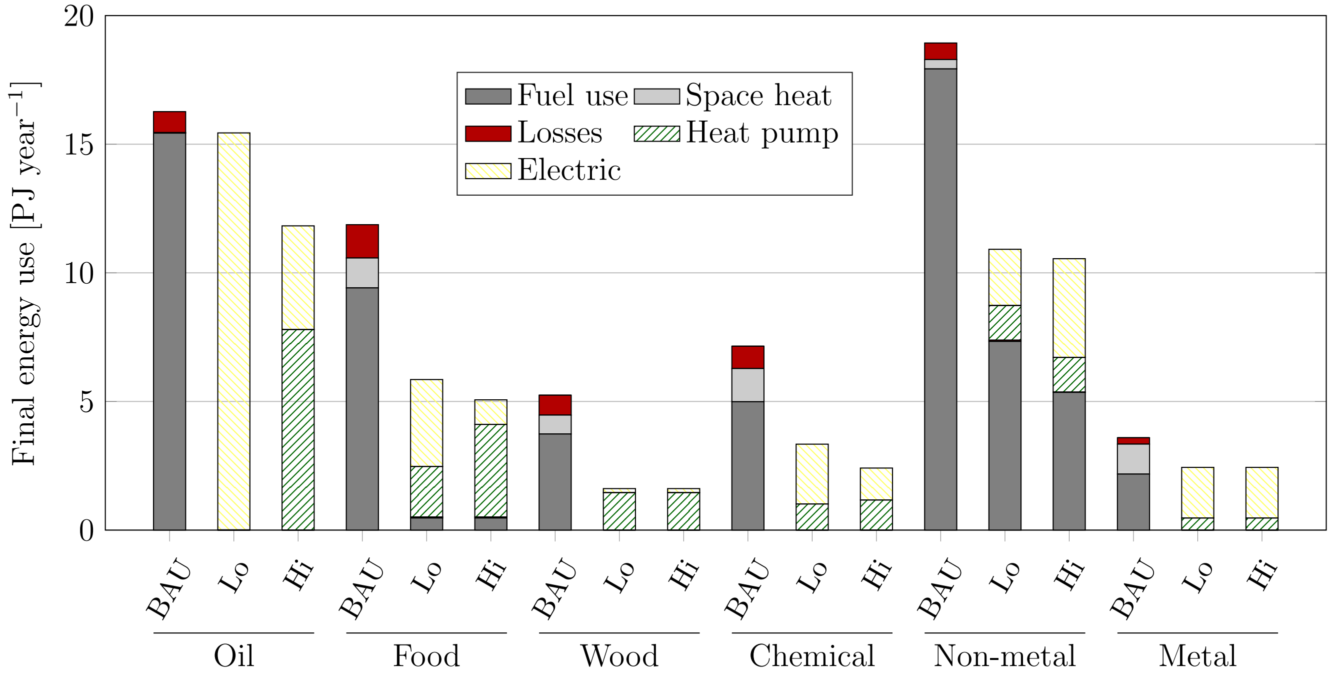
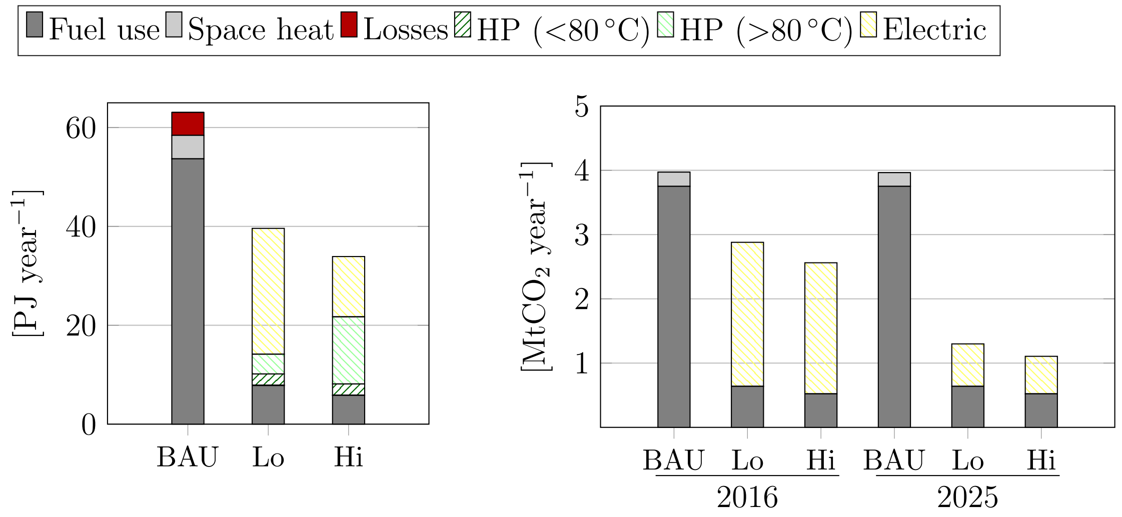


Figure 3: Final energy use for heating in the main industry sectors in Denmark for different scenarios. "BAU" desribes the current system, "Lo" and "Hi" the electrified systems.

whole, the final energy use can be reduced from 63 PJ to 34 PJ in the high and 40 PJ in the low scenario (Figure 4a). This does not indicate savings in energy use, but that some of the energy input is based on heat sources in heat pumps. These are assumed to be based on recovered excess heat or ambient sources. In the high scenario, heat pumps account for 47 % of the heat supply while this share is only 16 % in low scenario. The development of high temperature heat pumps thus has a high future potential.

There are further considerable reductions in CO_2-emission possible as shown in Figure 4b. With emission factors for 2016, the possible CO_2-emission reductions are between 27 % and 35 %. These reductions however primarily origin through the savings in final energy use, as the specific CO_2-emissions of electricity in Denmark were higher than the ones of natural gas. Towards 2025 however, the specific CO_2-emissions for electricity are expected to decrease considerably, which would result in a reduction of 70 % compared to the base line scenario.

The applied Lorenz efficiency of 45 % can be seen as a conservative estimate. Ranges between



(a) Final energy use

(b) CO_2-emissions

Figure 4: Final energy use and CO_2-emissions for heating in the Danish manufacturing industry in the current system (BAU) and electrified systems.

50 % and 60 % are possible [27]. An increase of the Lorenz efficiency to 50 % would reduce the electricity use in the Hi scenario by 6 % and an increase to 50 % would decrease electric energy use by 14 % compared to a Lorenz efficiency of 45 %. In the Lo scenario the decrease in electricity use would only by 2 % and 5 % respectively.

4.3. Economic electrification potential

The economic feasibility of electrifying a process or a complete industrial site depends on the relation of prices for electricity and fuels. The required investment costs determine the possible payback time of an investment. Other economic benefits, such as increased product throughput and quality, as well as additional income from providing balancing power to the grid will in some cases play an important role, but are neglected in the following.

Figure 5 presents the expected development of electricity and natural gas prices in Denmark for use in industrial processes until 2035 [28, 29]. The price for electricity used for process heating will decrease until 2020 due to tax reductions. The natural gas price is shown with and without the inclusion of CO_2 allowances as part of the EU emission trading system (EU ETS). Furthermore, a low price of 5 € per ton of CO_2 and a high price of 20 € per ton of CO_2 were chosen as a starting point in 2018. The low price represents initial estimations [28], while the high price represents the actual market situation [30]. From the ratio of electricity price to natural gas price (EL/NG), the minimum efficiency improvement required for obtain positive cashflows for the operation of the electricity based technologies can be found.

Assuming that the industry can accept a payback time of 3 years or 6 years for new electricity-based technologies, the maximum specific investment costs can be found in Figure 6. Electric boilers have investment costs between 70 € per kW and 150 € per kW of heating capacity [31]. Replacing existing natural gas boilers with electric ones, would reduce the final energy use by

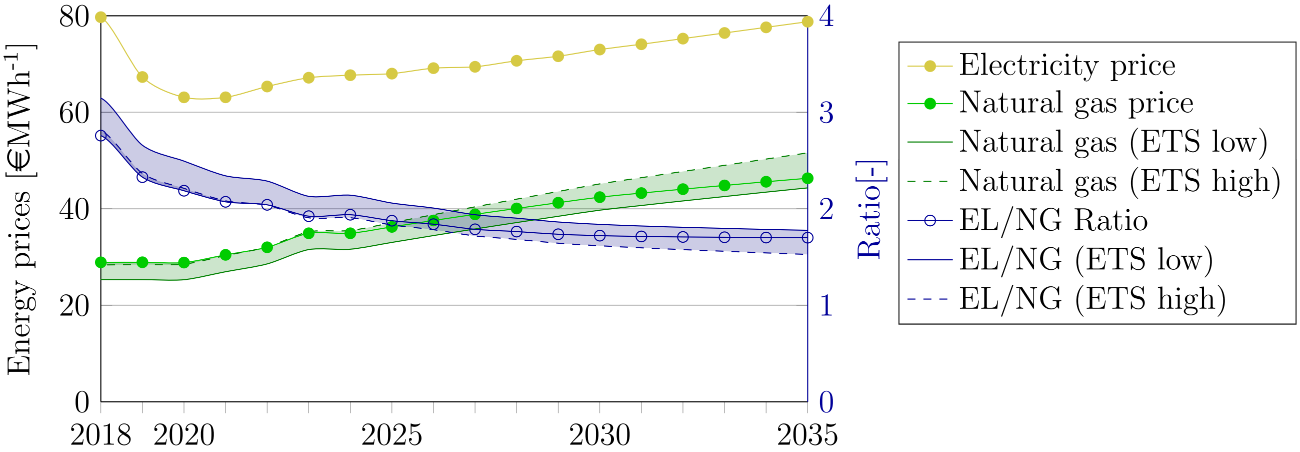
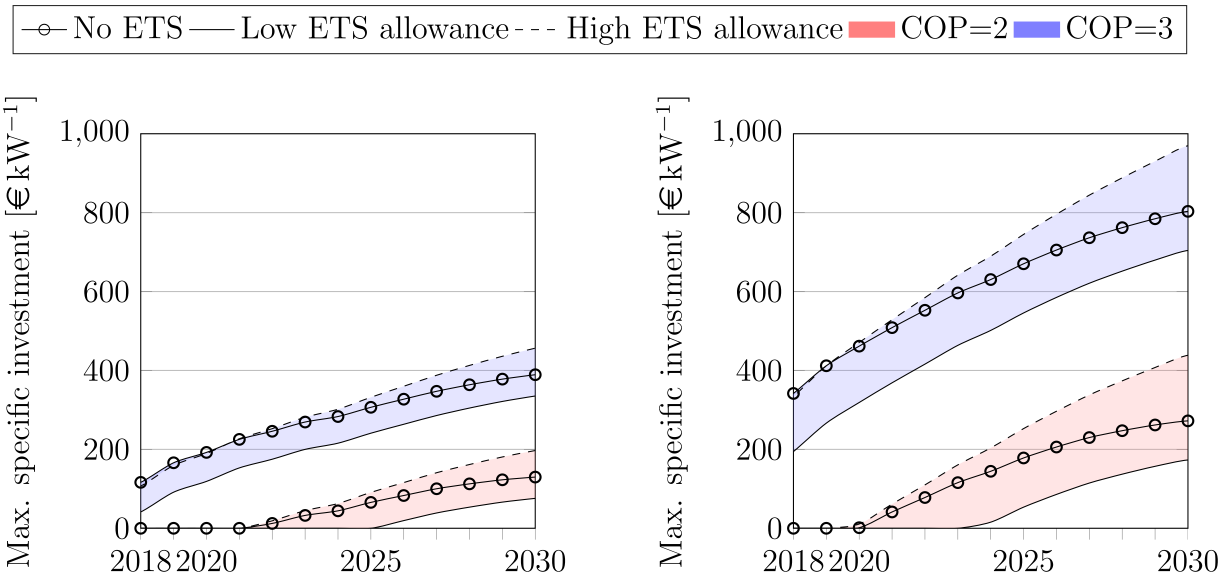


Figure 5: Development of energy prices for industrial process heat in Denmark until 2035 and the ratio between Electricity and natural gas. The addition of (ETS) indicates the inclusion of low and high costs for CO_2 allowances.



(b) Payback time 3 years

(c) Payback time 6 years

Figure 6: Maximum specific investment costs of new electric utility systems as a function of energy prices and efficiency of equipment for different payback times.

the amount of energy losses from the flue gas which would correspond to a COP of 1.05 using a natural gas boiler efficiency of 0.95. This investment would be infeasible under the shown economic frameworks. On the other hand, heat pumps for low temperature process heat have investment costs of 700 € per kW in 2015 which are expected to decrease to 590 € per kW in 2030. Their range of economic feasibility is considerably larger, as COP values of above 3 can be expected.

If the major driving force for the electrification of industrial processes is economic savings, a minimum COP of 2 will be required for electricity-based technology investments in the period between 2025 and 2030. Depending on the acceptable payback time of the investment and the specific investment costs, this value may be lower. By assuming that a minimum COP of 2 is required, the electrification potential found in the previous section is reduced. For the high technology development scenarios this means that 32 PJ of the final energy use will be fossil, compared to 5.9 PJ without economic constraints.

5. Discussion

The applied top-down approach used in this work to establish the electrification potential in Denmark shows that a large part of the industrial process energy use can be substituted by electricity and at the same time reduce the final energy use. While the overall electrification potential can be assessed accurately with the applied method, the performance of the technologies is quite uncertain. The COP of the heat pumps will depend on the availability and characteristics of heat sources at each industrial site. A more detailed assessment of opportunities to use electromagnetic technologies in the chemical, non-metallic mineral and metal industry is further required. In these industries higher reductions in final energy use could be possible. The future energy prices and technological developments have a high uncertainty, which will impact the economic electrification potential. The use of case studies, as part of a bottom-up approach, are required to specify and narrow down possible electrification technologies.

6. Conclusion

An increased use of electricity in the industry will be necessary to reduce its CO_2-emissions generated by burning fossil fuels. Besides this reduction, electrification can have other opportunities for industries, such as a reduction in final energy use, increase in production output or quality. In order to electrify an industrial site, meaning to adopt electricity-based technologies which replace fuel-based ones, a number of alternative technologies are available. The approach to identify the most optimal technologies and their integration requires further developments. On a national scale, the potential for electrification is significant as shown in previous studies for Germany and the Netherlands. In Denmark the majority of the manufacturing industry could be electrified, which would reduce the final energy use by more than one third. This reduction potential is a result of the large-scale integration of heat pumps, which can cover a substantial part of the process heating demand. With current and forecasted energy prices, the economic electrification potential is considerably lower based on assessment of economic feasibility only. The applied top-down approach to identify this potential should be complemented with case studies as part of a bottom-up analysis.

Acknowledgments

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Nomenclature

BAU Business as usual

COP Coefficient of performance

Hi High technology scenario

HP Heat pump

HTHP High temperature heat pump

IR Infrared

Lo Low technology scenario

MVR Mechanical vapour recompression

RF Radio frequency

References

[1] UNFCCC. Paris Agreement. *Conference of the Parties on its twenty-first session*, COP Report(U.N. Doc. FCCC/CP/2015/10/Add), dec 2015. ISSN 1098-6596. doi: FCCC/CP/2015/L.9/Rev.1.

[2] Cédric Philibert. Renewable Energy for Industry. From green energy to green materials and fuels. Technical report, International Energy Agency, Paris, 2017. URL `https://www.iea.org/publications/insights/insightpublications/Renewable{_}Energy{_}for{_}Industry.pdf`.

[3] IPCC. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014. ISBN 978-1-107-05821-7.

[4] Max Åhman, Lars J. Nilsson, and Bengt Johansson. Global climate policy and deep decarbonization of energy-intensive industries. *Climate Policy*, 17(5):634–649, 2017. ISSN 17527457. doi: 10.1080/14693062.2016.1167009.

[5] Max Åhman, Alexandra Nikoleris, and Lars J Nilsson. *Decarbonising industry in Sweden an assessment of possibilities and policy needs*. Number 77. Lund University, Lund, Sweden, 2012. ISBN 9789186961039. URL `https://www.naturvardsverket.se/upload/miljoarbete-i-samhallet/miljoarbete-i-sverige/klimat/fardplan-2050/decarbonising-industry-sweden-lunds-univ.pdf`.

[6] Anselm Eisentraut and Adam Brown. Heating without global warming - Market Developments and Policy Considerations for Renewable Heat. Technical report, International Energy Agency, 2014. URL `https://www.iea.org/publications/freepublications/publication/FeaturedInsight{_}HeatingWithoutGlobalWarming{_}FINAL.pdf`.

[7] Matthias Rehfeldt, Tobias Fleiter, and Felipe Toro. A bottom-up estimation of the heating and cooling demand in European industry. *Energy Efficiency*, 11(5):1057–1082, 2018. ISSN 15706478. doi: 10.1007/s12053-017-9571-y.

[8] Trieu Mai, Daniel Steinberg, Jeffrey Logan, David Bielen, Kelly Eurek, and Colin McMillan. An electrified future: Initial scenarios and future research for U.S. Energy and electricity systems. *IEEE Power and Energy Magazine*, 16(4):34–47, 2018. ISSN 15407977. doi: 10.1109/MPE.2018.2820445.

[9] Bert den Ouden, Niki Lintmeijer, Jort van Aken, Maarten Afman, Harry Croezen, Marit van Lieshout, Egbert Klop, René Waggeveld, and Jan Grift. Electrification in the Dutch process industry. Technical report, Netherlands Enterprise Agency (RVO), 2017.

[10] Beyond Zero Emissions. Zero Carbon Industry Plan: Electrifying Industry. Technical report, Melbourne, 2018. URL `http://bze.org.au/electrifying-industry-2018/`.

[11] Holger Wiertzema, Max Åhman, and Simon Harvey. Bottom-up methodology for assessing electrification options for deep decarbonisation of industrial processes. *Eceee Industrial Summer Study Proceedings*, pages 389–397, 2018. ISSN 20017987.

[12] EPRI. Program on Technology Innovation: Industrial Electrotechnology Development Opportunities. 2009. doi: 1019416.

[13] Anna Gruber, Franziska Biedermann, and Serafin von Roon. Industrielles Power-to-Heat Potenzial. In *9. Internationale Energiewirtschaftstagung an der TU Wien*, pages 1–20, 2015.

[14] Alexis Michael Bazzanella and Florian Ausfelder. Low carbon energy and feedstock for the European chemical industry. Technical report, DECHEMA e.V., Frankfurt am Main, 2017. URL `www.dechema.de`.

[15] Sebastiaan Hers, Maarten Afman, Sofia Cherif, and Frans Rooijers. Potential for Power-to-Heat in the Netherlands. Technical report, CE Delft, Delft, 2015.

[16] Trieu T Mai, Paige Jadun, Jeffrey S Logan, Colin A McMillan, Matteo Muratori, Daniel C Steinberg, Laura J Vimmerstedt, Benjamin Haley, Ryan Jones, and Brent Nelson. Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States. Technical report, National Renewable Energy Laboratory, Golden, CO, 2018. URL `https://www.nrel.gov/docs/fy18osti/71500.pdf`.

[17] Energistyrelsen. The future use of the gas infrastructure [In Danish: Den fremtidige anvendelse af gasinfrastrukturen]. Technical report, 2014. URL http://www.ens.dk/politik/dansk-klima-energipolitik/regeringens-klima-energipolitik/energiaftalens-analyser.

[18] Danish Energy Agency. Energy statistics 2016 [In Danish: Energistatistik 2016]. Technical report, 2017. URL http://www.ens.dk.

[19] Danish Energy Agency. Energy statistics 2017 [In Danish: Energistatistik 2017]. Technical report, Energistyrelsen,, Copenhagen, 2018. URL https://ens.dk/sites/ens.dk/files/Statistik/pub2017dk.pdf.

[20] Louise Hedelund Sørensen, Peter Maagøe Petersen, Søren Draborg, Kent Christensen, Kurt Mortensen, and Jørgen Pedersen. Mapping of energy use in companies [In Danish: Kortlægning af energiforbrug i virksomheder]. Technical report, Danish Energy Agency, Copenhagen, 2015. URL http://www.ens.dk/forbrug-besparelser/.

[21] Fabian Bühler, Tuong-Van Nguyen, and Brian Elmegaard. Energy and exergy analyses of the Danish industry sector. *Applied Energy*, 184:1447–1459, dec 2016. ISSN 03062619. doi: 10.1016/j.apenergy.2016.02.072. URL http://linkinghub.elsevier.com/retrieve/pii/S0306261916302094.

[22] Viegand Maagøe A/S. Analysis of possibilities for a better utilisaiton of excess heat from the industry [In Danish: Analyse af mulighederne for bedre udnyttelse af overskudsvarme fra industrien]. Technical Report August, Energistyrelsen, Copenhagen, 2013. URL https://ens.dk/ansvarsomraader/energibesparelser.

[23] Baijia Huang, Fabian Bühler, and Fridolin Müller Holm. Industrial Energy Mapping: THERMCYC WP6. Technical report, Technical University of Denmark, 2015. URL http://orbit.dtu.dk/files/128856759/INDUSTRIAL{_}ENERGY{_}MAPPING{_}THERMCYC{_}001b{_}fbu.pdf.

[24] IPCC. Volume 2: Energy - Chapter 2: Stationary Combustion. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, pages 2.1 – 2.47, 2006. ISSN 00218944. doi: 10.1016/S0166-526X(06)47021-5. URL https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2{_}Volume2/V2{_}2{_}Ch2{_}Stationary{_}Combustion.pdf.

[25] Energinet.DK. Environmental report for Danish electricity and combined heat and electricity [In Danish: Miljørapport for dansk el og kraftvarme]. Technical report, 2016. URL www.energinet.dk/milj.

[26] Stefan Lechtenböhmer, Lars J. Nilsson, Max Åhman, and Clemens Schneider. Decarbonising the energy intensive basic materials industry through electrification - Implications for future EU electricity demand. *Energy*, 115:1623–1631, 2016. ISSN 03605442. doi: 10.1016/j.energy.2016.07.110.

[27] Lars Reinholdt, B. Horntvedt, S.R. Nordtvedt, Brian Elmegaard, J.K. Jensen, and T.L. Lemminger. High temperature absorption compression heat pump for industrial waste heat. In *Proceedings of the 12th IIR Gustav Lorentzen Conference on Natural Refrigerants (GL2016)*, pages 1038–1045. International Institute of Refrigeration, 2016. ISBN 9782362150180. doi: 10.18462/iir.gl.2016.1175. URL `http://orbit.dtu.dk/en/publications/high-temperature-absorption-compression-heat-pump-for-industrial-waste-heat(b5350fc` `.html`.

[28] Danish Energy Agency. Socioeconomic calculation basis for energy prices and emissions [In Danish: Samfundsøkonomiske beregningsforudsætninger for energipriser og emissioner]. Technical report, Energistyrelsen, Copenhagen, 2017. URL `https://ens.dk/sites/ens.dk/files/Analyser/samfundsoekonomiske{_}beregningsforudsaetninger{_}2017.pdf`.

[29] PricewaterhouseCoopers. Overview for the accounting and reimbursement of taxes 2019 [In Danish: Samlet overblik over afregning og godtgørelse af afgifter 2019]. Technical report, Hellerup, 2018. URL `www.pwc.dk/da/afgifter/assets/pwc-afgiftsvejledning-2015.pdf`.

[30] European Energy Exchange AG. European Emission Allowances Auktion (EUA) Primary Market, 2019. URL `https://www.eex.com/en/market-data/environmental-markets/auction-market/european-emission-allowances-auction{#}!/2019/02/22`.

[31] Danish Energy Agency. Technology Data for Energy Plants - Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion. Technical Report March, 2015. URL `https://ens.dk/en/our-services/projections-and-models/technology-data`.

Elektrificering af processer og teknologier i dansk industri

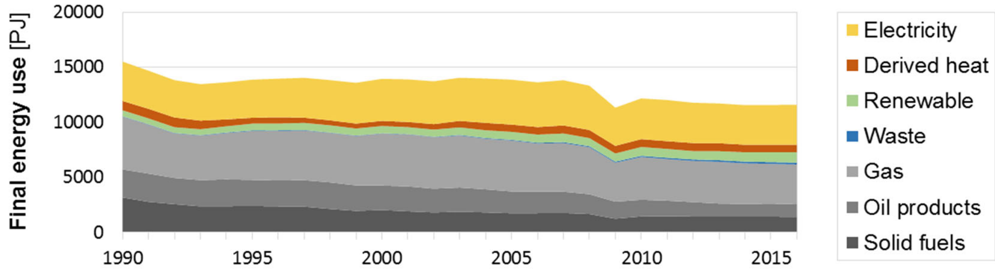
Potentials for the electrification of industrial processes in Denmark

Fabian Bühler, Fridolin Müller Holm and Brian Elmegaard

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

Introduction

Industrial energy use in EU-28:



- BAT in industry to reduce CO_2 – emissions by up to 15 – 30 %[1]
- Limited availability of bioenergy
- LCOE of many renewables in the range fossil fuel fired power generation[2]
- CO_2-emission factor in Denmark:
  - Natural gas: 0.204 tons per MWh
  - Electricity DK: 0.135 tons per MWh (2019)

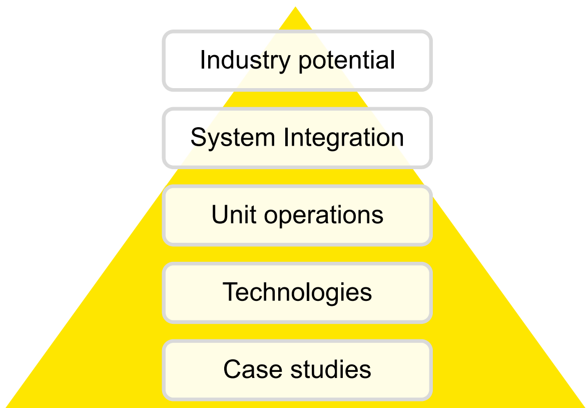
[1] IPCC (2014): Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

[2] IRENA (2019): Renewable Power Generation Costs in 2018.

Introduction

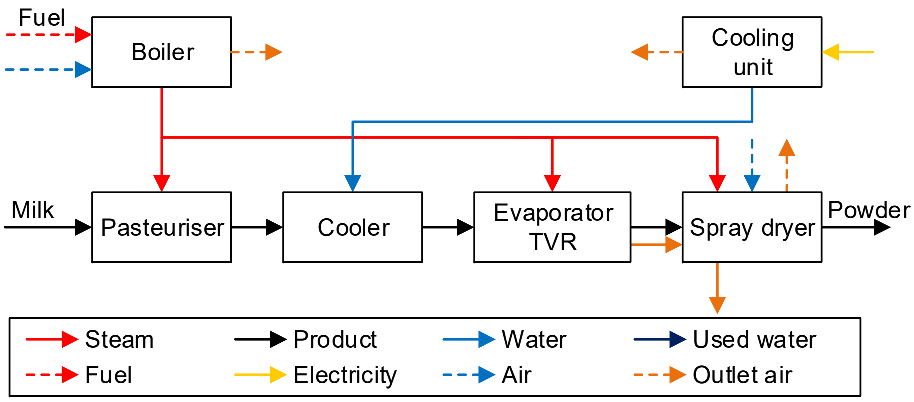
Objective
- Reduce energy use in thermal processes
- Electrification options and technologies
- **Potential for electrification in industry**
- Challenges and boundary conditions for electrification

Approach



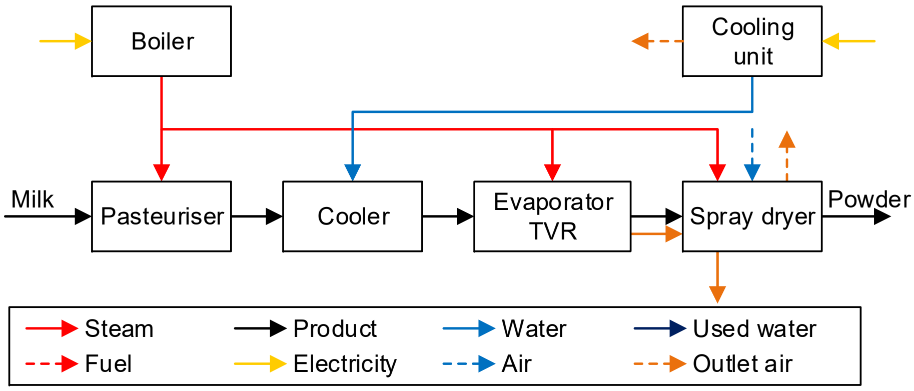
Electrification of industrial processes

- Electrofuels



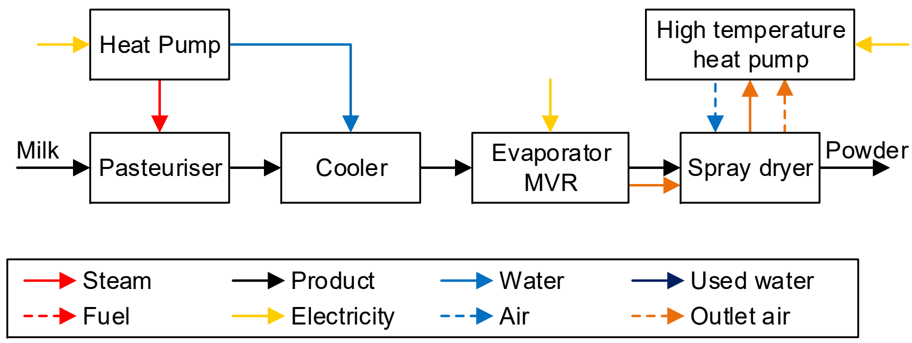
Electrification of industrial processes

- Power to fuel
- Power to heat (central): Electric boiler, heat pump



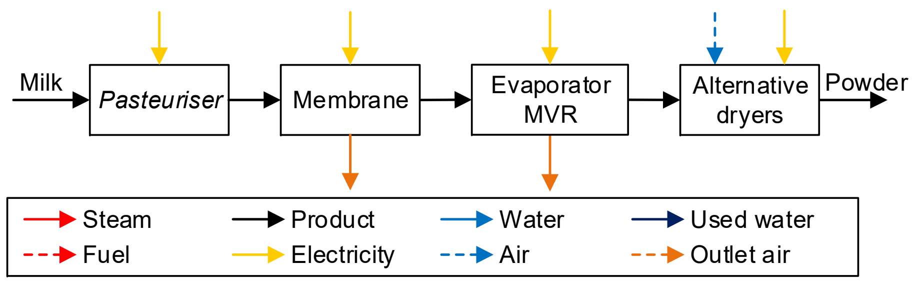
Electrification of industrial processes

- Power to fuel
- Power to heat (central)
- Power to heat (process): Heat pump, resistance heating, electromagnetic (e.g. microwave, IR, RF)



Electrification of industrial processes

- Power to fuel
- Power to heat (central)
- Power to heat (process)
- Power to Y: Pressure, irradiation, UV, electric field, freeze drying



Electrification of industrial processes

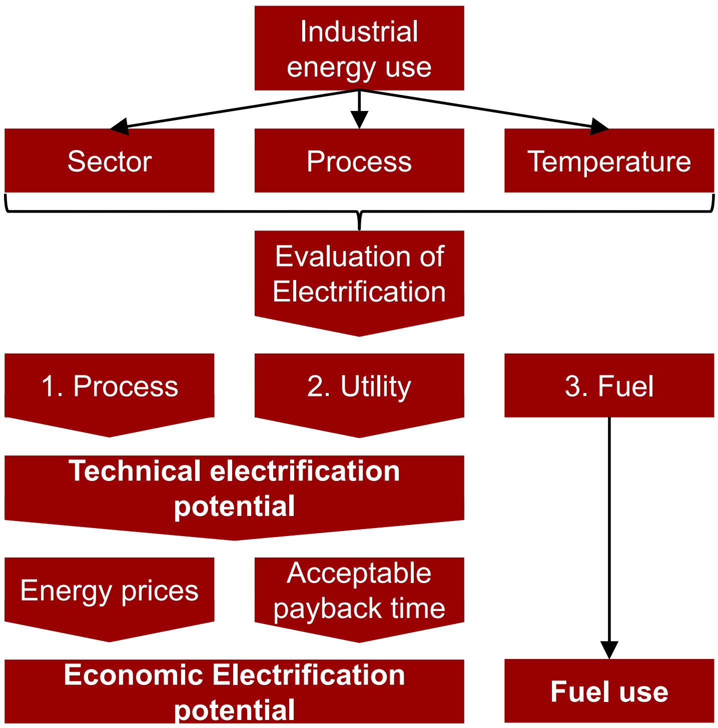
- Power to fuel
- Power to heat (central)
- Power to heat (process)
- Power to Y

Energy use

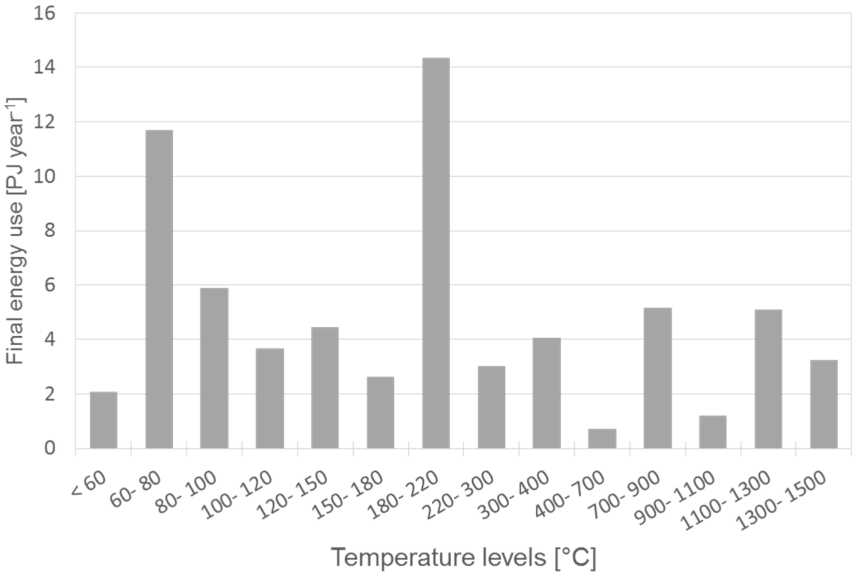
Changes in production

Required Innovation/ R&D potential

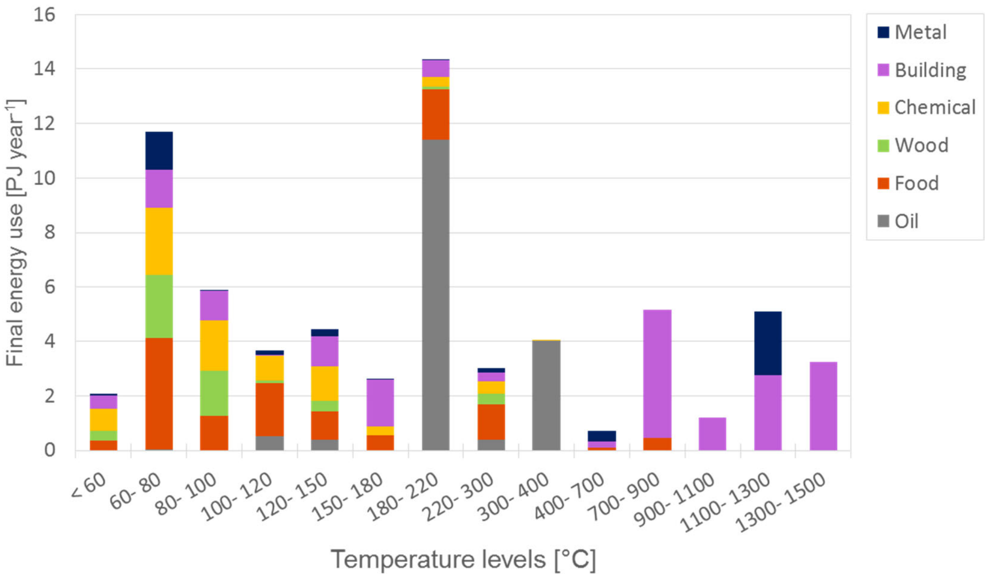
Approach
Establishing electrification potential



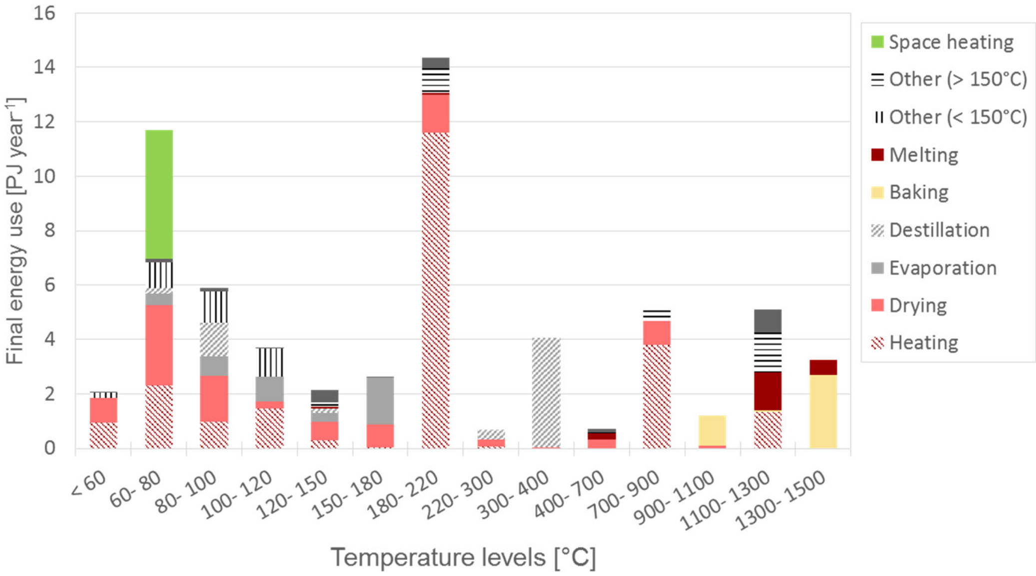
Industrial energy use in Denmark



Industrial energy use in Denmark



Industrial energy use in Denmark



Evaluation of electrification options

Process and utility

- Heat Pumps for process heat
  – Process heat demand < 80 °C and space heating
    - Lower temperature heat sources at 10 °C
  – Process heat demand > 80 °C
    - Heat source temperature gradually increasing up to 80 °C
  – COP with Lorenz efficiency of 0.5
- MVR (Mechanical Vapour Recompression)
- VRC HIDiC (Vapour Recompression Heat integrated distillation)
- Electric heaters, boilers and electrode boilers

Special processes

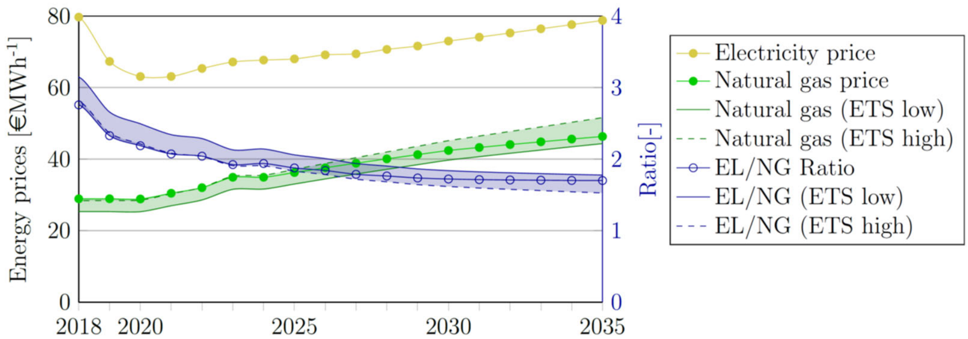
- Brick production -> Microwave assisted kiln
- Cement production -> Clinker heating
- Drying of metal paints -> IR drying
- Melting e.g. Aluminium -> Induction furnaces

Scenario and economic analysis

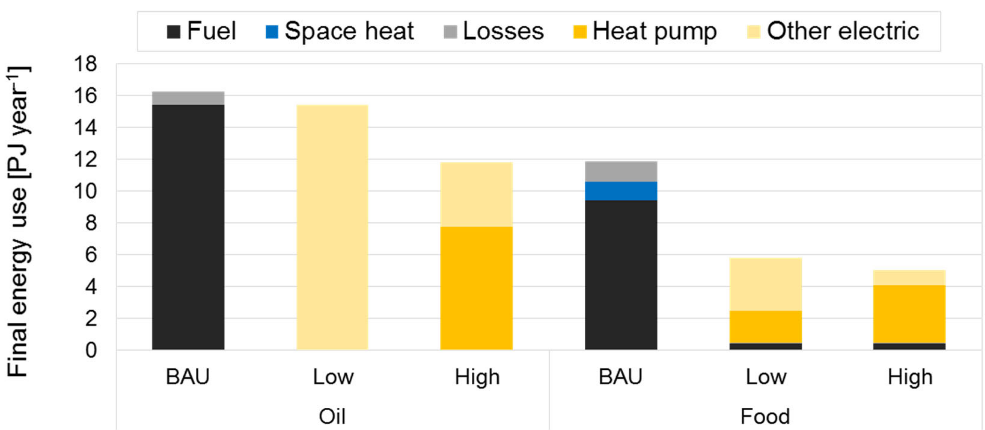
Technology scenarios:

- **Low** technological development scenario
- **High** technological development scenario

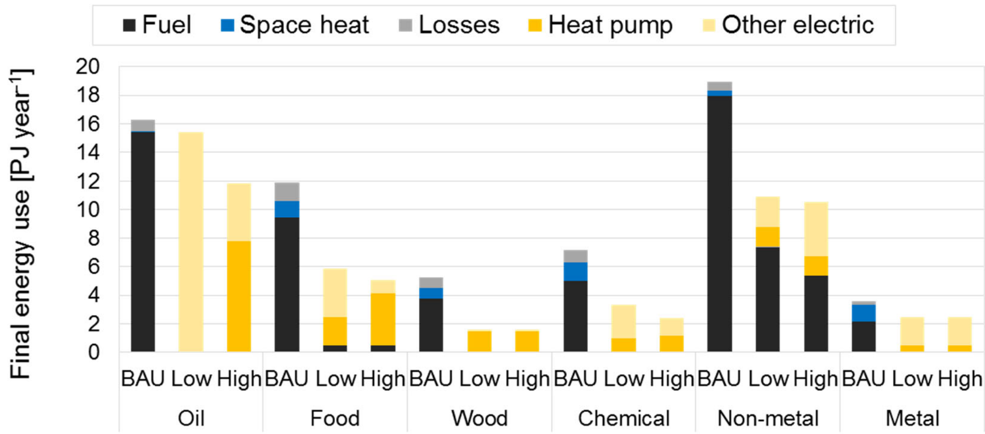
Energy price scenarios:



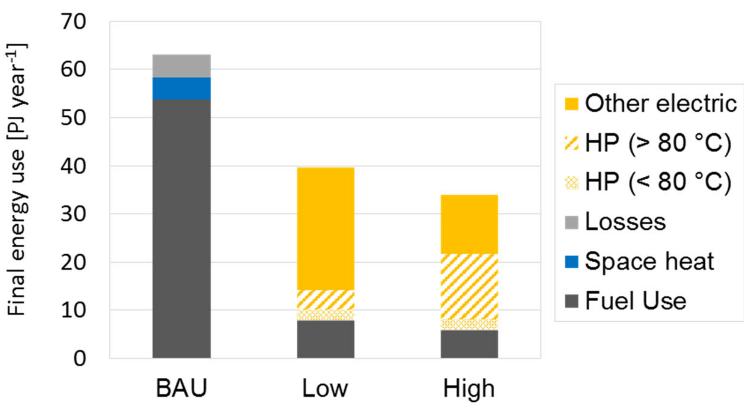
Electrification potential



Electrification potential

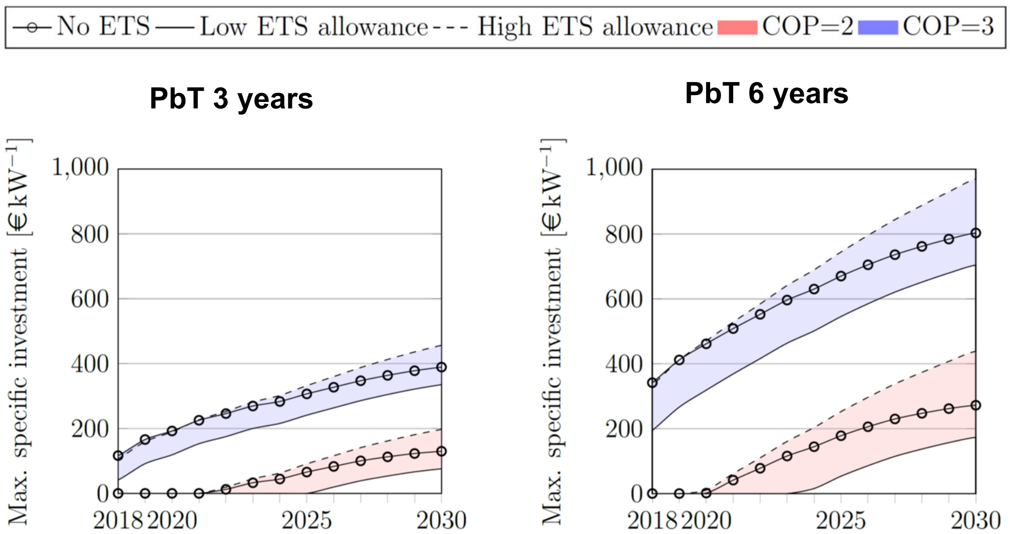


Electrification potential

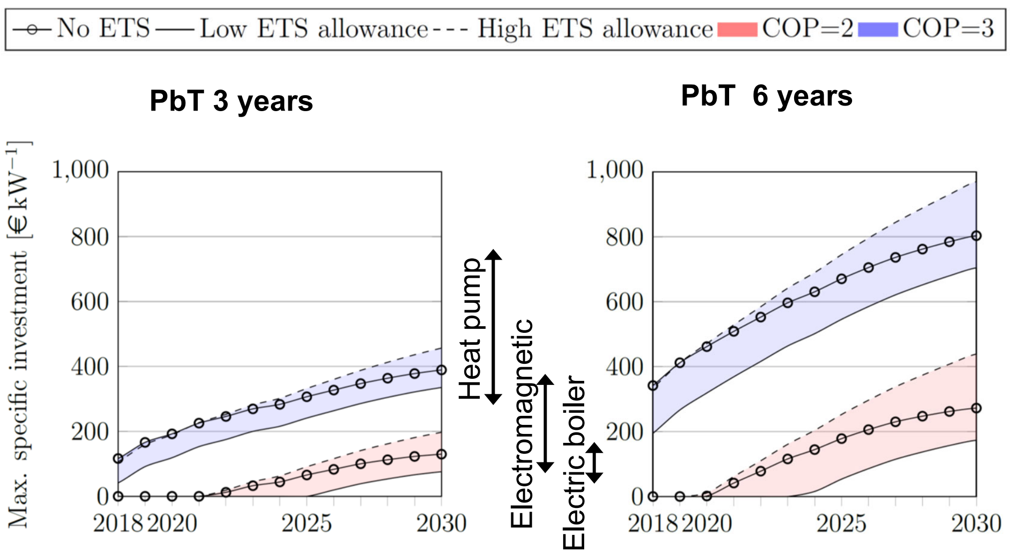


- CO_2-emission reduction from electrification
  - 2016: 28% to 36%
  - 2025: 68% to 72%

Economic electrification potential



Economic electrification potential



Final remarks

- Future industrial sectors and processes different then today
- Sector coupling and flexibility of power to heat in industry
- Denmark with high low temperature heating demand
  - High electrification potential with existing technologies in Denmark
  - Reduction in final energy use
- Performance of technology uncertain
  - Available heat sources
  - Replacement of processes

Thank you for your attention!

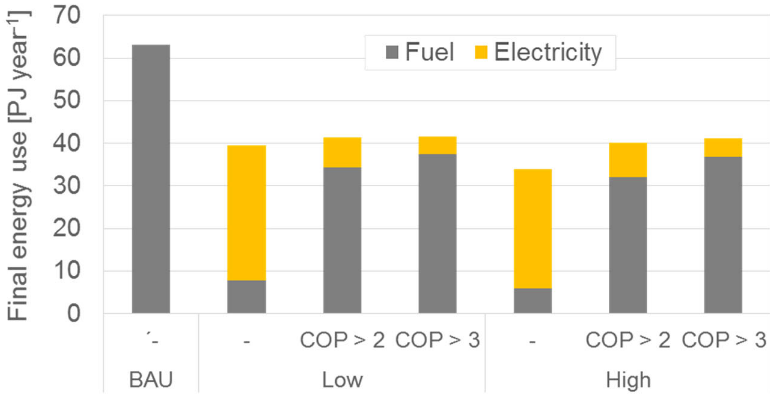
Fabian Bühler

Danish Energy Agency

FNBR@ens.dk

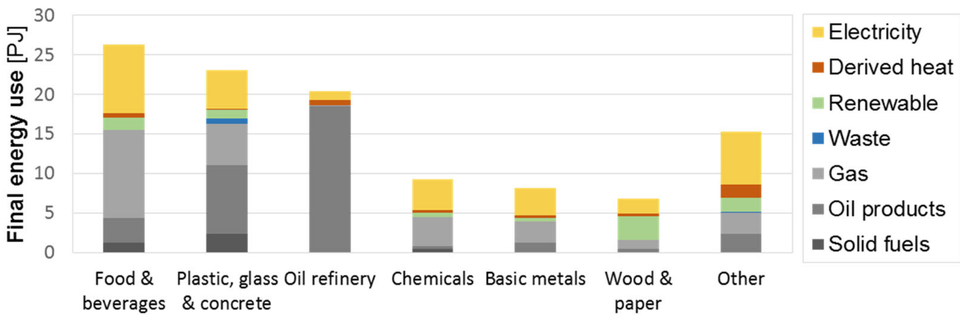
+45 22471020

Economic electrification potential

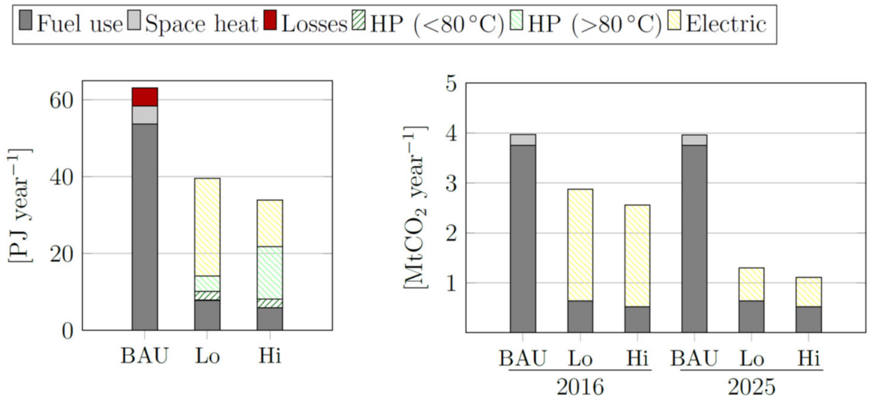


- Final energy use almost constant
- Share of electricity decreases substantially

Energy use by source and sector in DK



Results

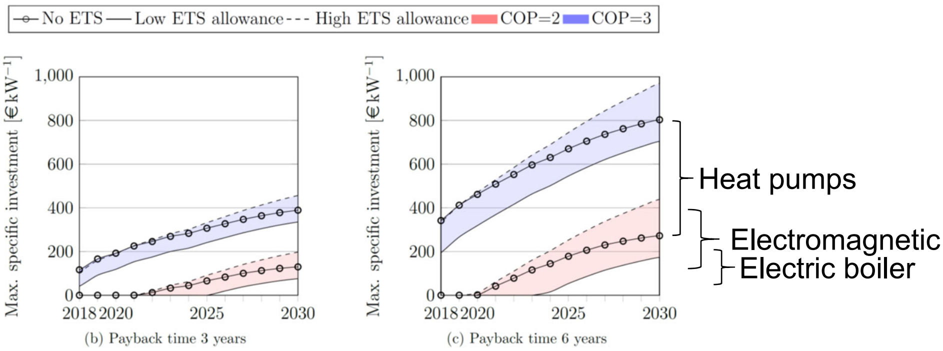


(a) Final energy use (b) CO_2-emissions

Technology Overview

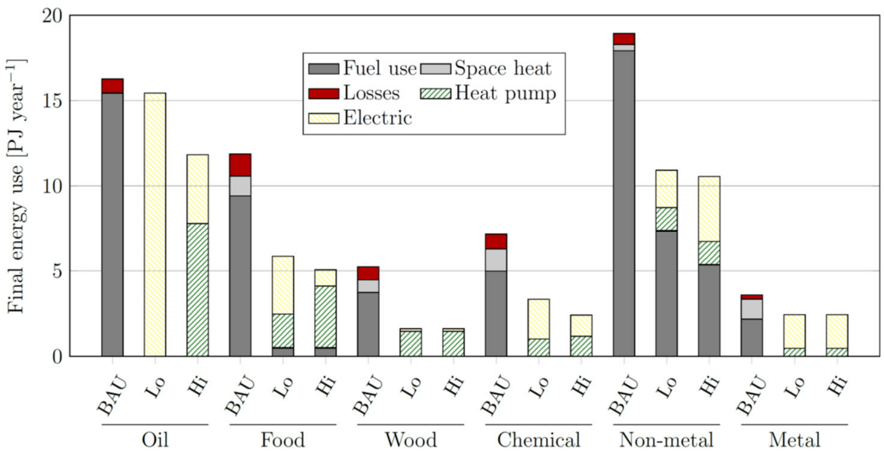
Process	Technology	Availability	Output
Process heat (steam, water)	Heat pump	High	
	HTHP	Medium	
	Electric boiler	High	
	Electrode Boiler	High	
	Vapour recompression	High	
-Drying	Electromagnetic	Medium	+
	Impulse drying	Low	
	Impingement drying	Low	
-Sterilisation/ pasteurisation	Electromagnetic	Medium	+
	High pressure sterilisation	Low	
-Distillation/ separation	Filtration	Medium	
	Electrical field/ electrostatic	Low	
	Mechanical techniques	Medium	
Baking/ melting/ casting	Induction furnace	High	+
	Electromagnetic	Medium	+
	Direct/ indirect resistance	High	+
	Electric arc furnace	High	
	Plasma heating	Medium	
	Electron beam heating	Medium	+

Results
Economic electrification potential

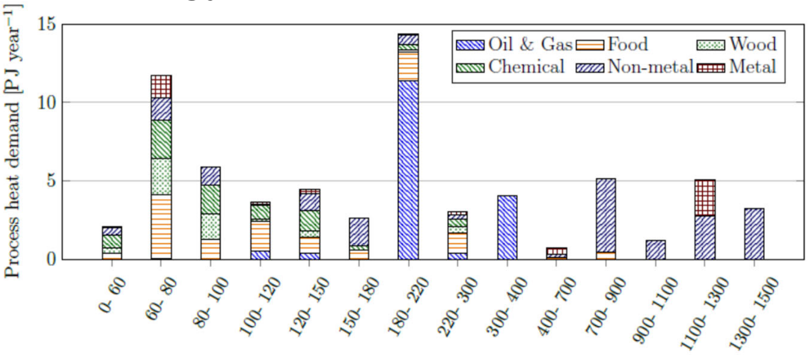


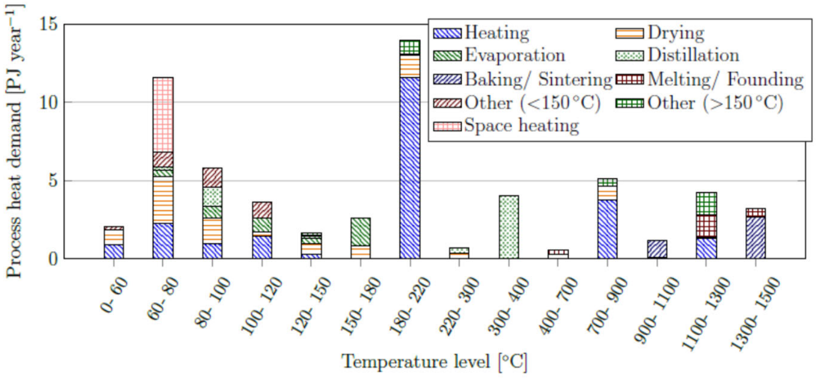
	Min. COP	Fuel Use [PJ]	Electricity Use [PJ]	Fuel use reduction
BAU	-	63.1	-	-
Hi	-	5.9	28.0	91%
	2	32.0	8.1	49%
	3	36.8	4.3	42%
Lo	-	7.9	31.7	87%
	2	34.3	7.1	46%
	3	37.4	4.1	41%

Results



Method
Industrial energy use in Denmark





The potential of heat pumps in the electrification of the Danish industry

Fabian Bühler[1], *Benjamin Zühlsdorf*[2], *Fridolin Müller Holm*[3] *and Brian Elmegaard*[1]

[1] Technical University of Denmark, Department of Mechanical Engineering, Lyngby, Denmark, fabuhl@mek.dtu.dk
[2] Technological Institute, Energy and Climate, Aarhus, Denmark, bez@teknologisk.dk
[3] Viegand Maagøe A/S, Copenhagen, Denmark, fmh@vmas.dk

Keywords:
High temperature heat pump, electrification, industry, Denmark

Introduction

Reaching the goals set by the Paris Agreement (UNFCCC, 2015) requires the energy sector to have net-zero CO_2-emissions the latest by 2060 (Philibert, 2017). The power sector changes from fossil fuels to renewable energy sources, providing increasing amounts of clean energy. The decarbonisation of the industry sector is however often overseen, despite the industry accounting for 21 % of the direct global greenhouse gas emissions in 2010 (IPCC, 2014). A decarbonisation of the industry can happen on a large scale following three main technology options, (i) the replacement of fossil fuels with bioenergy, (ii) the electrification of processes and (iii) the implementation of carbon capture and storage technologies (Åhman et al., 2012). Electrification of processes reduces energy-related CO_2-emissions, but it can also reduce the final energy use by integrating heat pumps (HP). The choice of Power-to-Heat technologies generally depend on process and temperature requirements. Some promising electrification technologies, such as high temperature heat pumps (HTHP) or heat pump-assisted distillation, have currently a low technology readiness level (den Ouden et al., 2017), while other available technologies, such as electric boilers and Mechanical Vapour Recompression (MVR), can be infeasible under current economic conditions. The potential for HTHPs was investigated for the European industry (Kosmadakis, 2019), where it was found that HTHP can cover about 1.5 % of the industries heat consumption.

This work derives an overview of the potential of heat pump-based process heat supply for the electrification of thermal processes in the Danish industry.

Energy use in the Danish manufacturing industry

In Denmark, the share of electricity in final energy use of the manufacturing industry has increased from 27.1 % in 1990 to 32.5 % in 2017 (Danish Energy Agency, 2018). The share of natural gas has increased in the same period from 31.3 % to 20.8 %, while the use of oil drastically decreased. The total share of fossil fuel directly used for heating in the industry was still around 50 % in 2017.

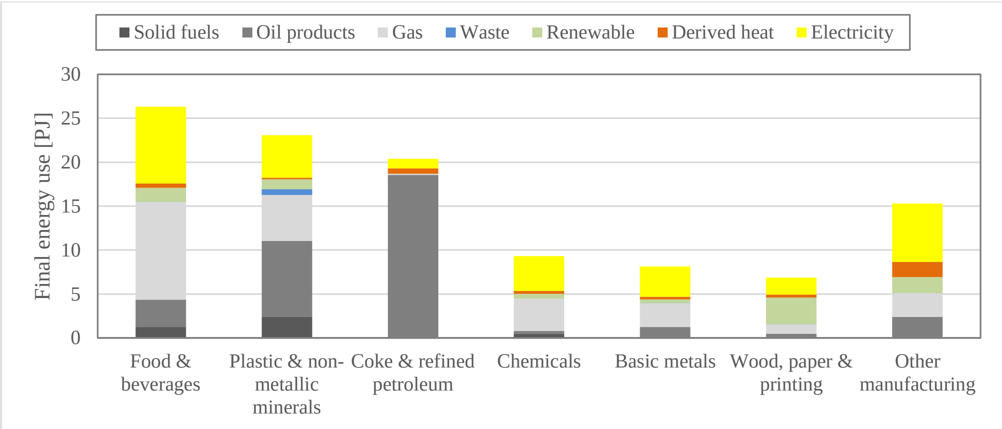


Figure 1: Total final energy use in the Danish industry by industrial sector and energy carrier in 2016 (Denmark Statistics, 2017)

In Figure 1 it can be seen that there are three main industrial sectors in terms of energy use, namely the food and beverage sector, mainly consisting of the production of dairy, meat, beverages and other food products. In the second most energy intense category, the manufacturing of concrete and bricks represents the highest share in terms of fuel use and the most energy intense sector overall with a total fuel use of 17 PJ in 2016.

Processes energy use in the Danish industry

In Figure 2 the process heat demand in the Danish manufacturing industry is shown by temperature level and process. It can be seen that below 100 °C heat is required amongst others for drying and distillation. Heat at higher temperatures is used for also for baking and melting. The peak between 180 °C and 220 °C originates from heating process in refineries and process heat supply. Figure 1

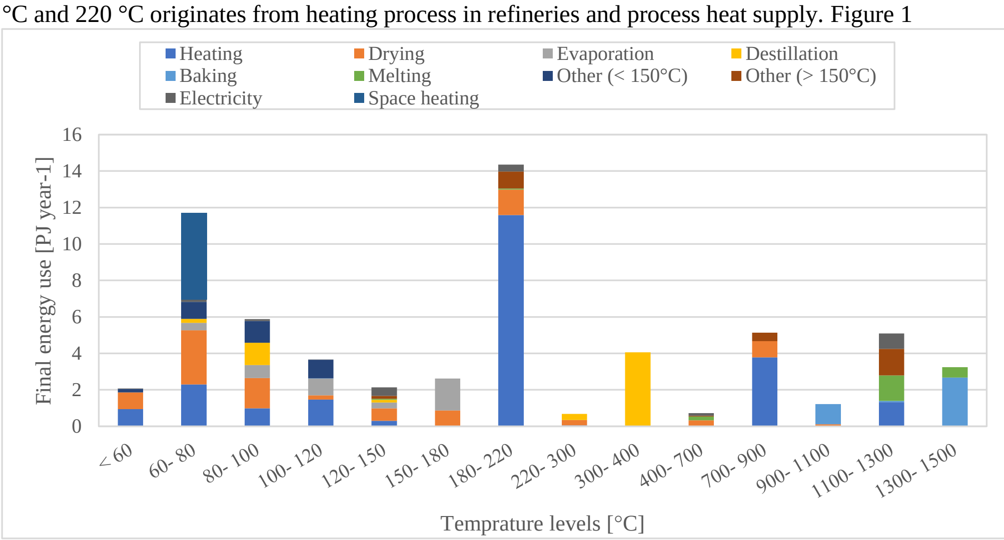


Figure 2: Final energy use of the 21 most energy intense manufacturing industries by temperature and process (Bühler et al., 2016a; Sørensen et al., 2015).

Heat pump potential for waste heat recovery in the Danish manufacturing industry

Figure 3 and 4 describe the amount of heat that could be supplied to industrial processes considering that the available excess heat and temperatures. It further shows the median obtainable COP and the distribution shown in the 1st and 3rd quartile (25 and 75 percentile)

The potential for utilising excess heat with heat pumps in the Danish industry was done based on the work published in (Bühler et al., 2016b). First the amount of excess heat was estimated based on process energy use (Sørensen et al., 2015) for each process in the 22 industrial sector with the highest energy use. Excess heat and process heat were split in up into three temperature levels for each process. Based on these numbers the potential for upgrading the excess heat with a heat pump was evaluated. A simplified heat pump model consisting of the Lorenz COP and a heat pump efficiency of 0.55 was used. It was assumed that excess heat can only be used for the same process type. As the temperatures required generalisation, it was assumed that the excess heat is always cooled down to a reference temperature of 15 °C. Two cases where assumed for the heat sink: (i) it was assumed that the sink is heated from the excess heat temperature to the maximum heat pump supply temperature or the process heat temperature if below the maximum supply temperature, (ii) it was assumed that all heat is supplied at the lower of the maximum heat pumps supply temperature or required process heat temperature. The results are shown for the cases in Figure 3 and Figure 4.

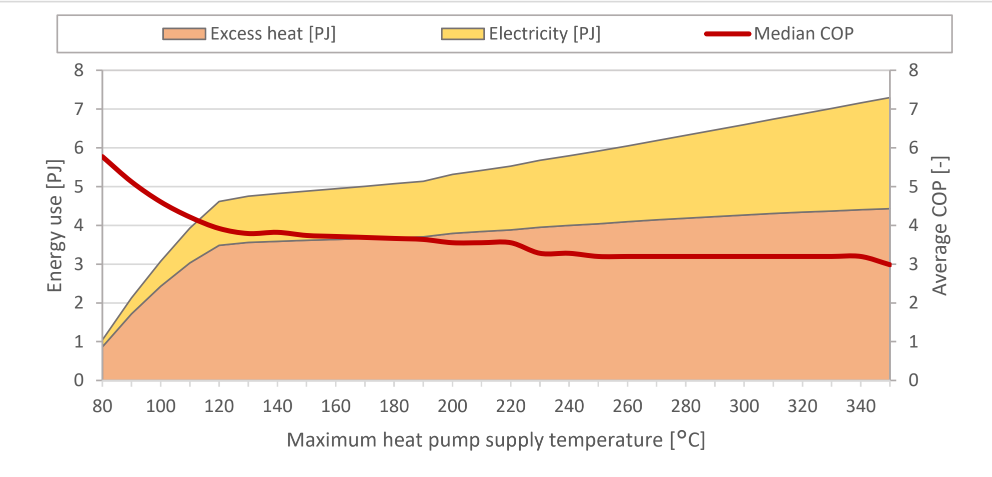


Figure 3: Utilisation potential of excess heat with heat pumps and average COP in the Danish manufacturing industry assuming the heat pump sink is heated from the excess heat temperature to the maximum supply temperature.

It can be seen that for a glide on the heat sink, there is a very sharp increase in the amount of process heat that could be supplied by heat pumps that are recovering excess heat. The lower increase above 120 °C is caused by the requirement of processing heating below this temperature and the decreasing availability of excess heat at temperatures above. From 120 °C onwards, the used excess heat increases slightly while the COP decreases, increasing the overall amount of process heat supplied over proportionally.

The same increase until 120 °C can be observed in Figure 4, where the heat is provided at the highest temperature without glide. However the amount of utilised excess heat is almost constant thereafter, as the obtainable COP are very low and thereby increase the heat supply covering the process heat demands.

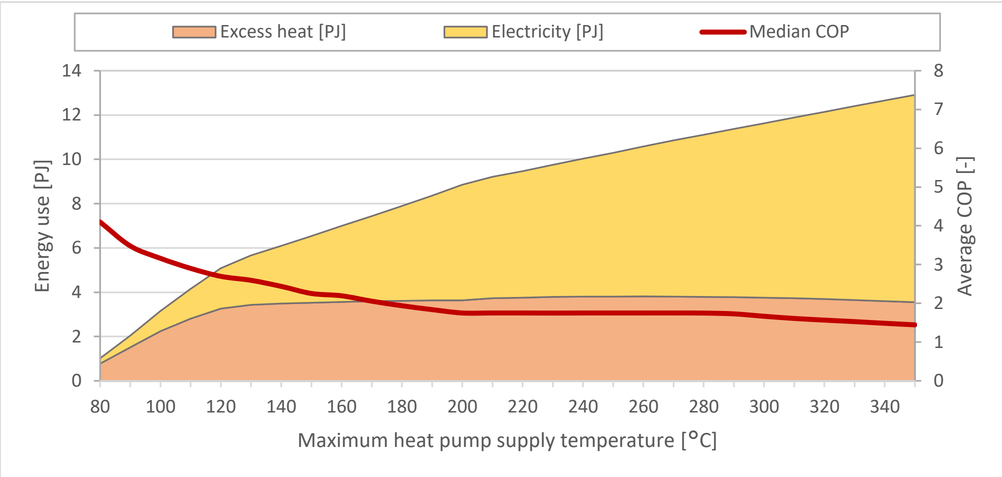


Figure 4: Utilisation potential of excess heat with heat pumps and average COP in the Danish manufacturing industry assuming all heat is supplied at the maximum heat pump supply temperature.

The differences in Figure 3 and 4 are mainly related to the different assumptions with respect to the heat supply. While it was assumed in Figure 3, that the heat is supplied to a medium that is heated from the excess heat temperature to the maximum process heat temperature, it was assumed in Figure 4 that the entire heat is supplied at the maximum process heat temperature. The assumption from Figure 3 corresponds to e.g., heating a single phase medium such as drying air, while the assumption from Figure 4 may be correct in case of process heat supply by steam.

Excess heat sources for heat pumps

The total excess heat found was further spatially distributed to individual production sites following the approach described in (Bühler et al., 2017). Finally, production profiles for industrial sectors were created to determine the peak excess heat. Profiles were created to describe main industry activities and to represent the size of industries (e.g. number of shifts). This approach was based on (Bühler et al., 2018; Wiese and Baldini, 2018). Initially this data and methods were used to find the potential of utilising excess heat for district heating, but are used in the following to give an impression of excess heat rates in the industrial sector.

Figure 5 and Figure 7 show the distribution of excess heat sources across heat rate intervals by temperature of the excess heat and by main industry sector. Similarly, Figure 6 and Figure 8 show the total excess heat potential by temperature and main industrial sector in these intervals. While the majority of the sources are below 100 kW, the highest excess heat potential is found in sources above 1 MW. Temperatures are relatively even distributed, however the small sources are mainly from food, chemical and wood processing industries. The large sources are exclusively found in oil refineries and non-metal mineral processing. It is however possible that in industries, excess heat from small sources is bundled and emitted from a single source.

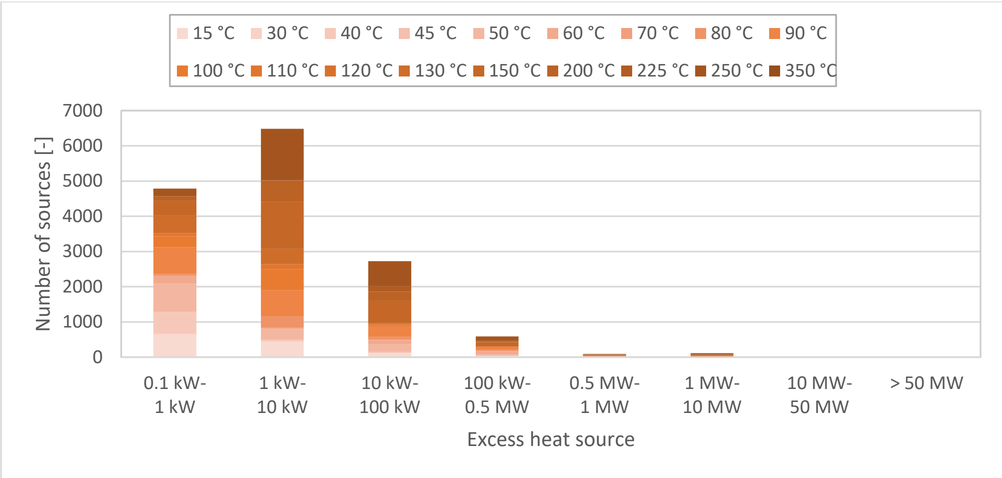


Figure 5: Distribution of excess heat sources from thermal processes in the Danish manufacturing industry (number of sources).

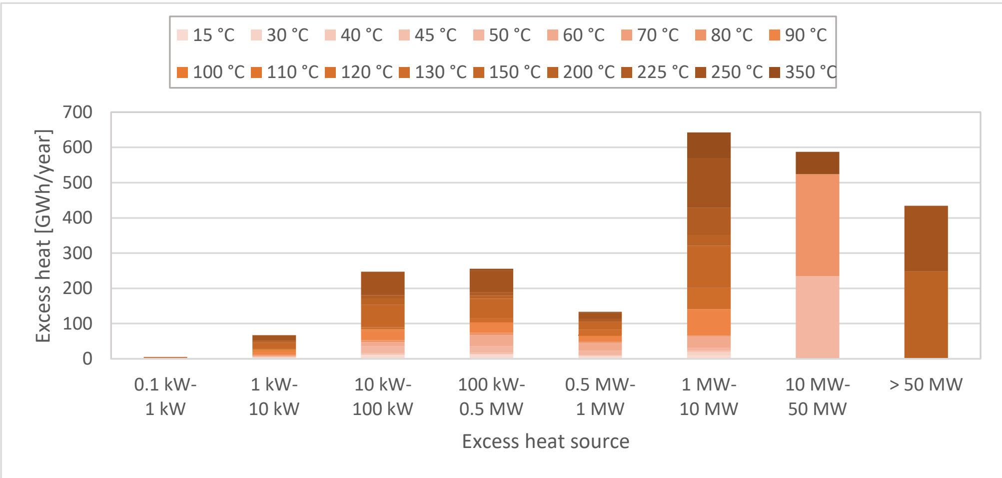


Figure 6: Distribution of excess heat sources from thermal processes in the Danish manufacturing industry (excess heat potential).

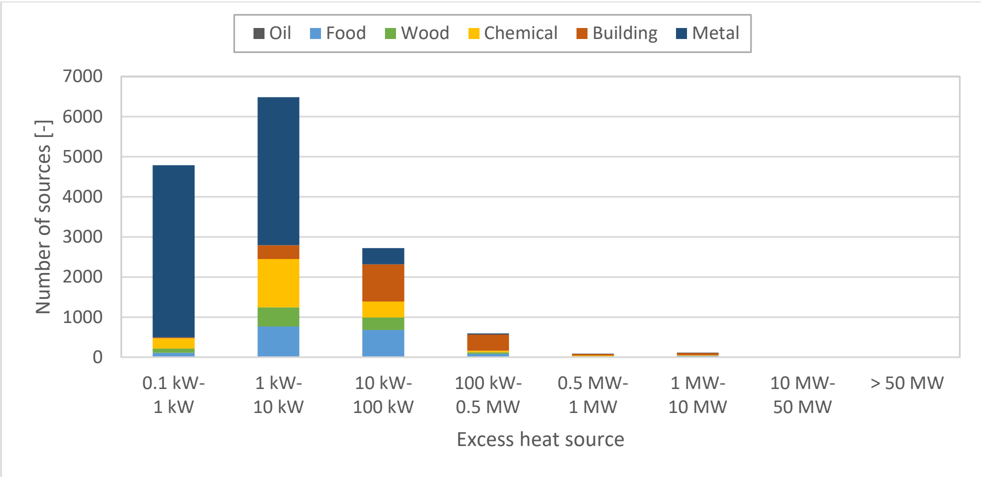


Figure 7: Distribution of excess heat sources from thermal processes in the Danish manufacturing industry (number of sources).

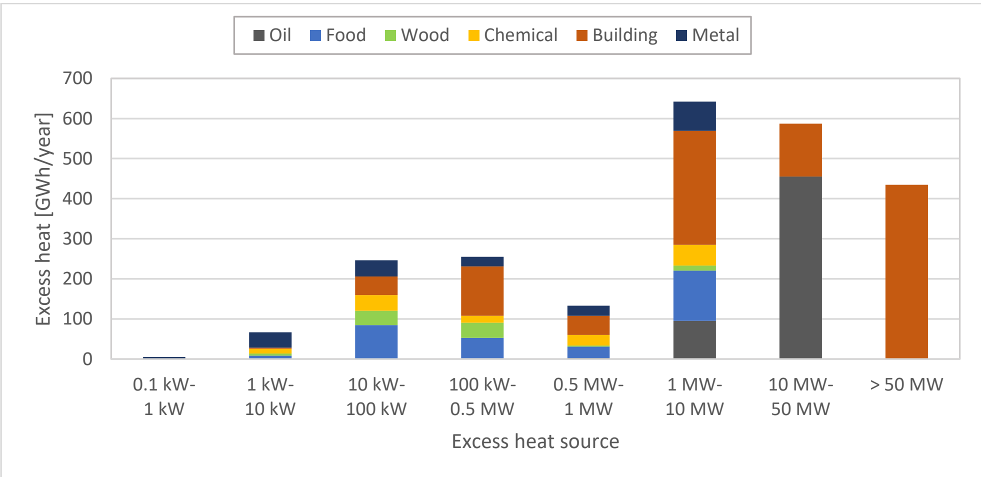


Figure 8: Distribution of excess heat sources from thermal process in the Danish manufacturing industry.

Conclusion

This work showed that heat pumps in the Danish industry, which can provide process heat at up to 120 °C can utilise a significant amount of excess heat to supply process heat. Technologies supplying higher temperatures have a possible potential if lower COPs are accepted. The final potential depends however on the matching of heat source and sink, as well as the heat sink characteristics. For high temperature heat pumps, due to economy of scale, particularly large excess heat sources will be of interest. The number of excess heat sources from thermal processes in the industry above 1 MW is limited to a few (below 150), however they represent a significant amount of the total available heat in Denmark.

References

Åhman, M., Nikoleris, A., Nilsson, L.J., 2012. Decarbonising industry in Sweden an assessment of possibilities and policy needs. Lund University, Lund, Sweden.

Bühler, F., Nguyen, T. Van, Elmegaard, B., 2016a. Energy and exergy analyses of the Danish industry sector. Appl. Energy 184, 1447–1459. doi:10.1016/j.apenergy.2016.02.072

Bühler, F., Nguyen, T. Van, Elmegaard, B., 2016b. Energy and exergy analyses of the Danish industry sector. Appl. Energy 184, 1447–1459. doi:10.1016/j.apenergy.2016.02.072

Bühler, F., Petrović, S., Holm, F.M., Karlsson, K., Elmegaard, B., 2018. Spatiotemporal and economic analysis of industrial excess heat as a resource for district heating. Energy 151, 715–728. doi:10.1016/j.energy.2018.03.059

Bühler, F., Petrović, S., Karlsson, K., Elmegaard, B., 2017. Industrial excess heat for district heating in Denmark. Appl. Energy 205, 991–1001. doi:10.1016/j.apenergy.2017.08.032

Cooper, S.J.G., Hammond, G.P., Hewitt, N., Norman, J.B., Tassou, S.A., Youssef, W., 2019. Energy saving potential of high temperature heat pumps in the UK Food and Drink sector. Energy Procedia 161, 142–149. doi:10.1016/j.egypro.2019.02.073

Danish Energy Agency, 2018. Energy statistics 2017 [In Danish: Energistatistik 2017]. Copenhagen.

den Ouden, B., Lintmeijer, N., van Aken, J., Afman, M., Croezen, H., van Lieshout, M., Klop, E., Waggeveld, R., Grift, J., 2017. Electrification in the Dutch process industry.

Denmark Statistics, 2017. ENE2HA: Energy Account in common units (detailed table) by use and type of energy [WWW Document]. URL www.statistikbanken.dk/ENE2HA (accessed 10.30.17).

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kosmadakis, G., 2019. Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries. Appl. Therm. Eng. 156, 287–298. doi:10.1016/j.applthermaleng.2019.04.082

Philibert, C., 2017. Renewable Energy for Industry. From green energy to green materials and fuels, International Energy Agency. Paris.

Sørensen, L.H., Maagøe Petersen, P., Draborg, S., Christensen, K., Mortensen, K., Pedersen, J., 2015. Mapping of energy use in companies [In Danish: Kortlægning af energiforbrug i virksomheder]. Copenhagen.

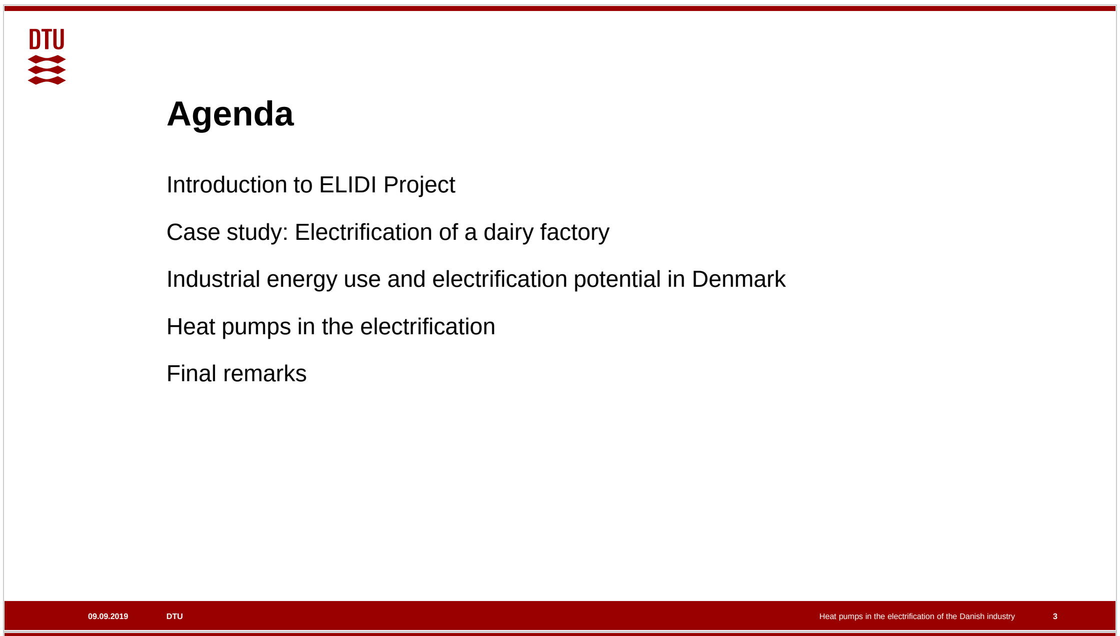
UNFCCC, 2015. Paris Agreement. Conf. Parties its twenty-first Sess. COP Report. doi:FCCC/CP/2015/L.9/Rev.1

Wiese, F., Baldini, M., 2018. Conceptual model of the industry sector in an energy system model: A case study for Denmark. J. Clean. Prod. 203, 427–443. doi:10.1016/j.jclepro.2018.08.229

2nd Conference on High Temperature Heat Pumps (HTHP)
9th of September 2019, Copenhagen

The potential of heat pumps in the electrification of the Danish industry

Fabian Bühler, Technical University of Denmark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Agenda
Introduction to ELIDI Project
Case study: Electrification of a dairy factory
Industrial energy use and electrification potential in Denmark
Heat pumps in the electrification
Final remarks
09.09.2019
DTU
Heat pumps in the electrification of the Danish industry
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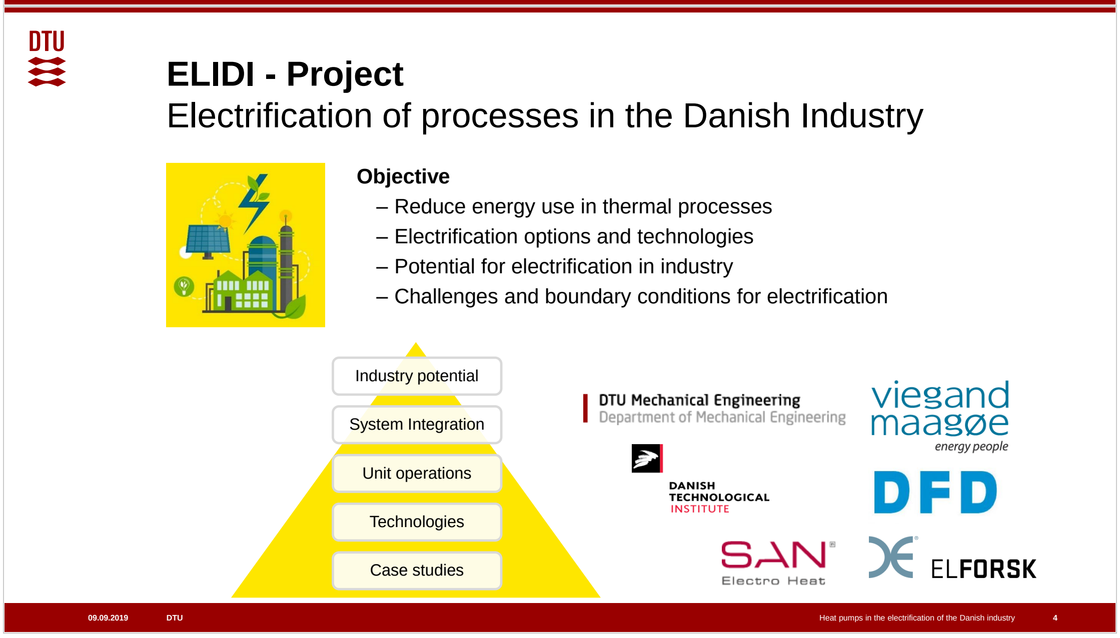
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ELIDI - Project
Electrification of processes in the Danish Industry
Objective
– Reduce energy use in thermal processes
– Electrification options and technologies
– Potential for electrification in industry
– Challenges and boundary conditions for electrification
Industry potential
System Integration
Unit operations
Technologies
Case studies
DTU Mechanical Engineering
Department of Mechanical Engineering
viegand maagøe
energy people
DANISH TECHNOLOGICAL INSTITUTE
DFD
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Electro Heat
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Heat pumps in the electrification of the Danish industry
4

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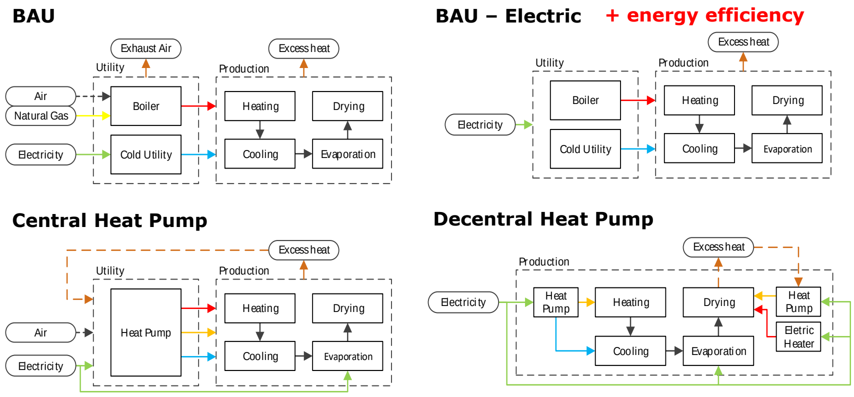
Electrification of dairy factory (milk powder)

Possible strategies



09.09.2019 DTU Heat pumps in the electrification of the Danish industry 5

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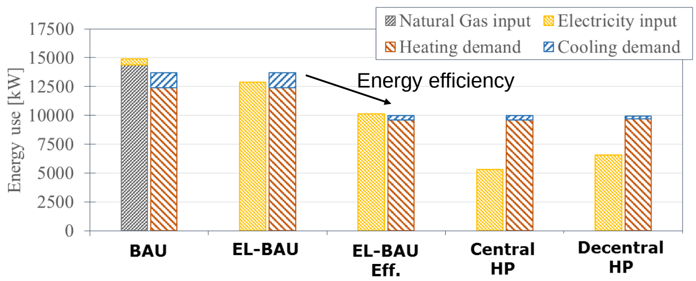
Electrification – Dairy factory

Energy analysis



- Central heat pump: System COP of 1.95
- Decentral heat pump: System COP of 1.57
  Individual COP between 1 and 5.2
- Cooling demand covered with HP

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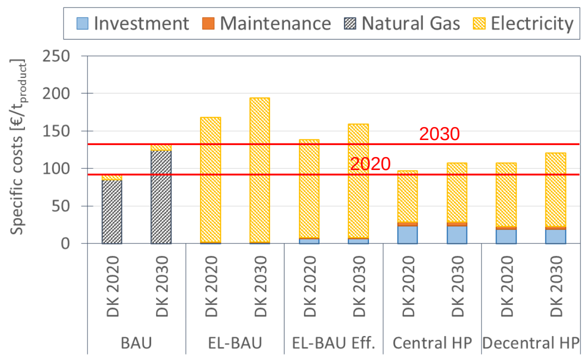
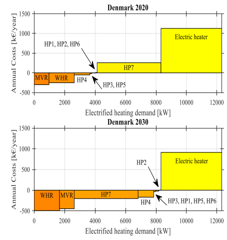
Electrification – Dairy factory

Economic analysis



Simple payback time

- DK 2030 (rplacing existing boiler):
  - Central 8 years
  - Decentral 10 years



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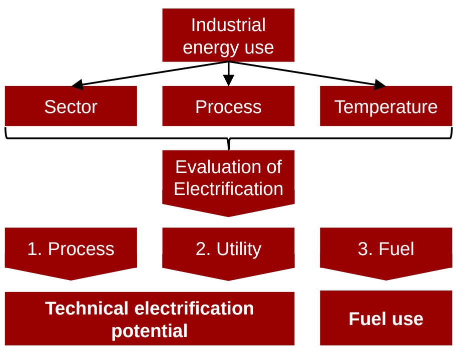
Electrification potential in Denmark

Approach



Process and utility

- Heat Pumps for process heat
  - Heat demand < 80 °C
    - Heat sources at 10 °C
  - Heat demand > 80 °C
    - Heat source gradually increasing up to 80 °C
- MVR, VRC HIDiC
- Electric heaters, boilers

Special processes

- Brick production (Microwave assisted kiln)
- Cement production (Clinker heating)
- Drying of metal paints (IR drying)
- Melting (Induction furnaces)

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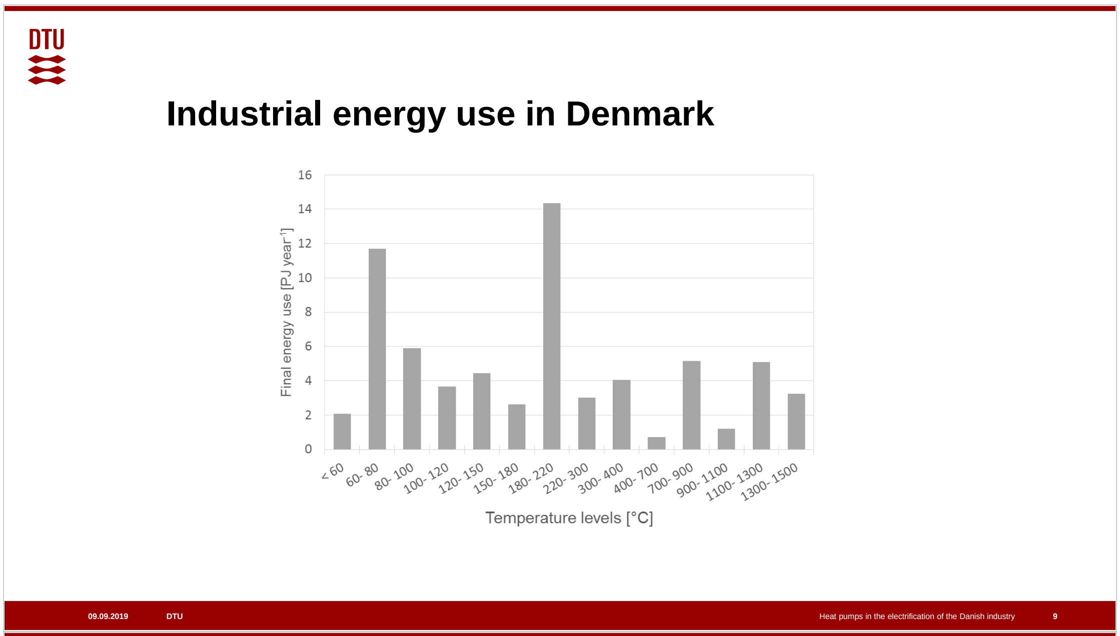
Industrial energy use in Denmark
Final energy use [PJ year⁻¹]
16
14
12
10
8
6
4
2
0
< 60
60- 80
80- 100
100- 120
120- 150
150- 180
180- 220
220- 300
300- 400
400- 700
700- 900
900- 1100
1100- 1300
1300- 1500
Temperature levels [°C]
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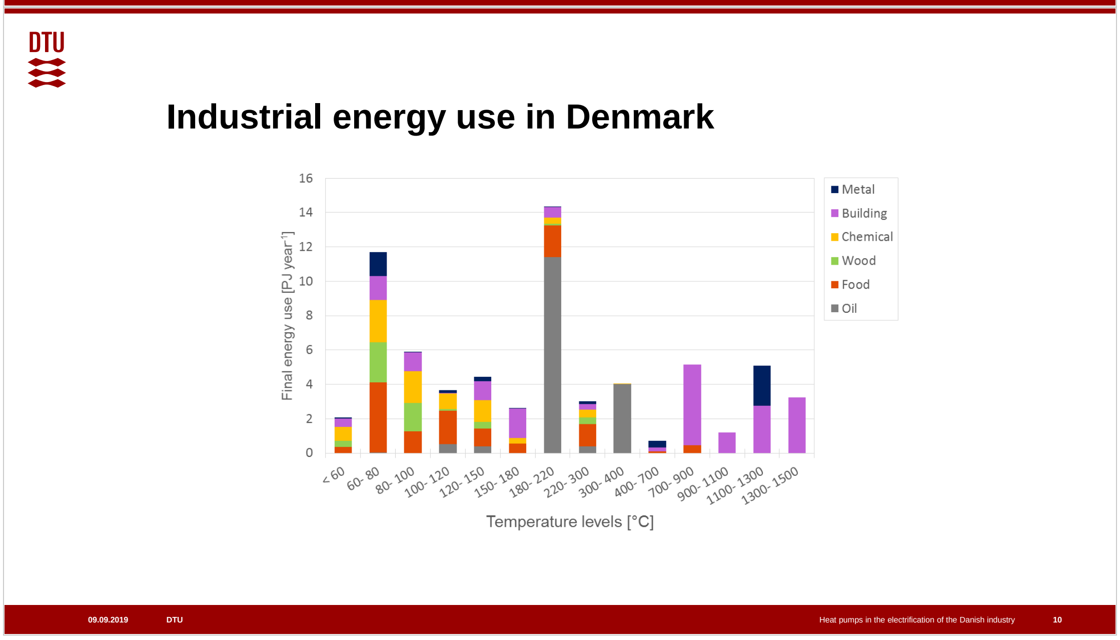
Industrial energy use in Denmark
Final energy use [PJ year⁻¹]
16
14
12
10
8
6
4
2
0
< 60
60- 80
80- 100
100- 120
120- 150
150- 180
180- 220
220- 300
300- 400
400- 700
700- 900
900- 1100
1100- 1300
1300- 1500
Temperature levels [°C]
Metal
Building
Chemical
Wood
Food
Oil
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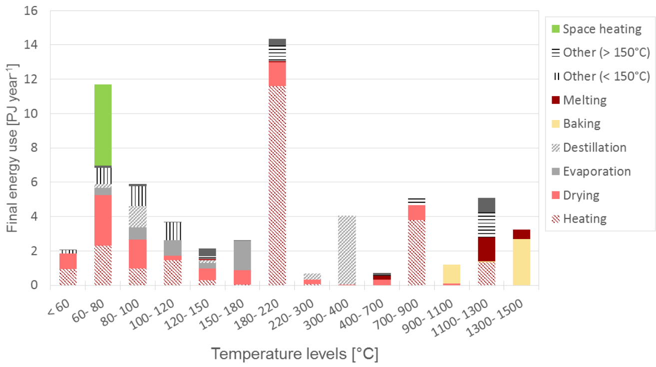
Industrial energy use in Denmark



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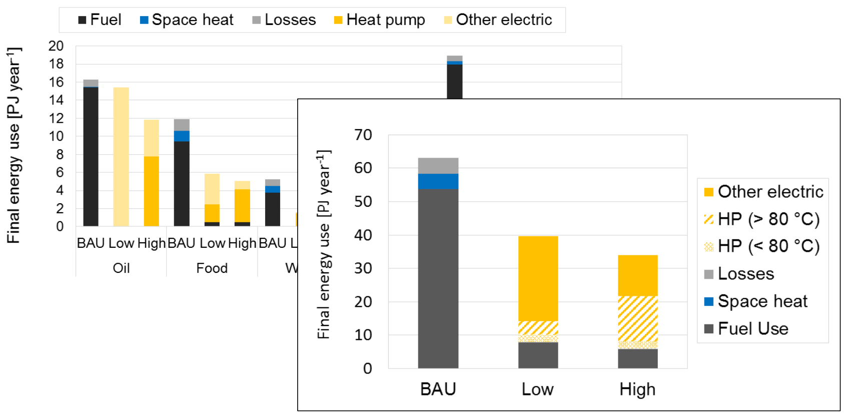
Electrification potential in Denmark



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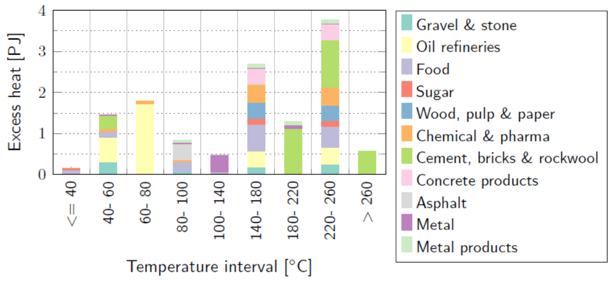
Excess heat in Denmark



Excess heat in Denmark	212.0	PJ per year
manufacturing industry	23.0	PJ per year
thermal processes	12.6	PJ per year

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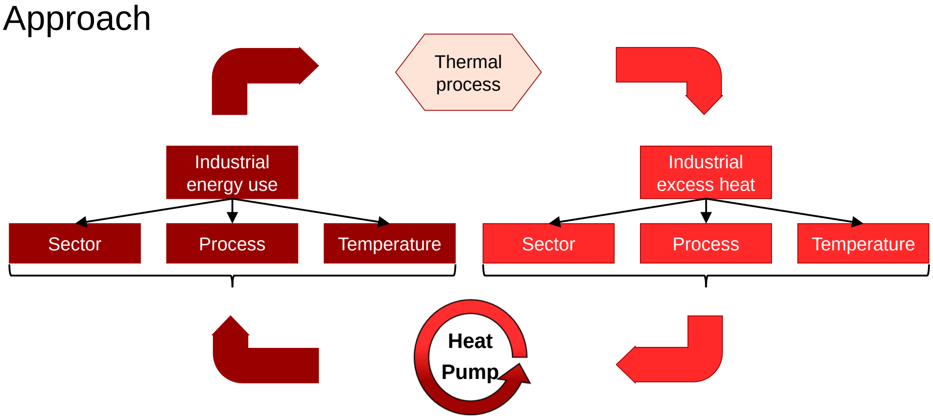
Electrification potential in Denmark

Approach



- Max. supply temperature
- Temperature lift

- Lorenz Cycle

- Outlet temperature

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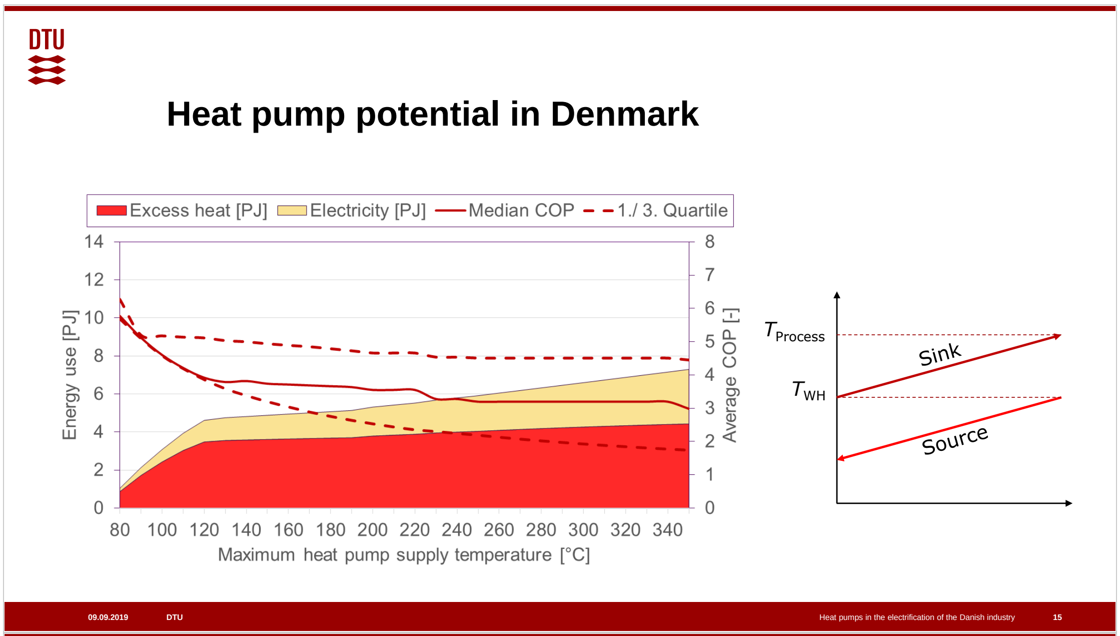
DTU
Heat pump potential in Denmark
Excess heat [PJ]
Electricity [PJ]
Median COP
1./ 3. Quartile
Energy use [PJ]
Average COP [-]
Maximum heat pump supply temperature [°C]
0
2
4
6
8
10
12
14
80
100
120
140
160
180
200
220
240
260
280
300
320
340
T_{Process}
T_{WH}
Sink
Source
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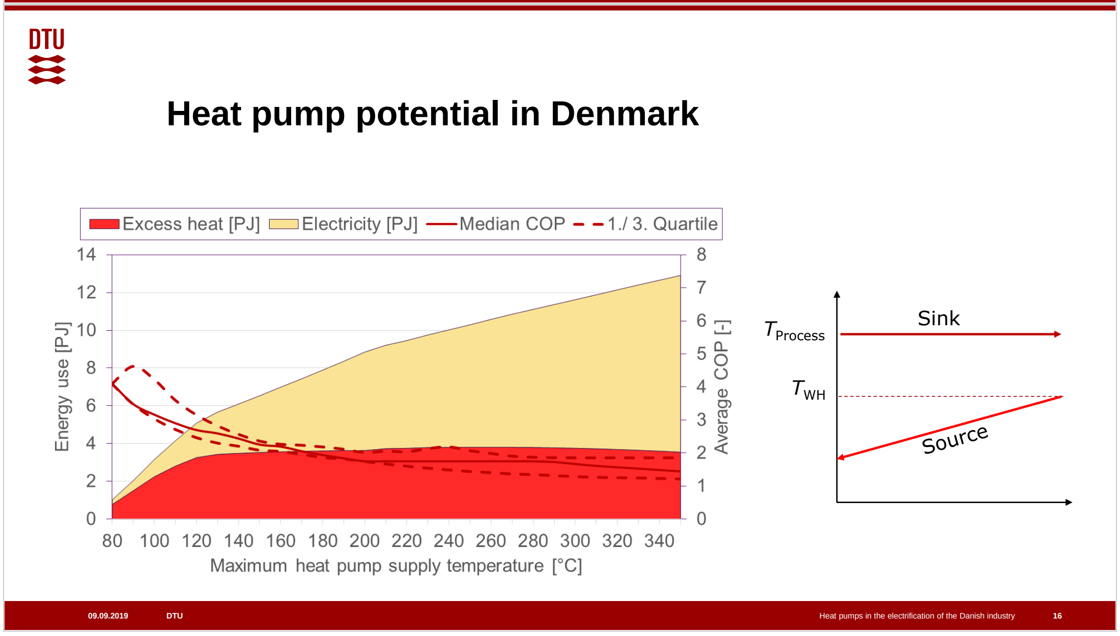
Heat pumps in the electrification of the Danish industry
15


DTU
Heat pump potential in Denmark
Excess heat [PJ]
Electricity [PJ]
Median COP
1./ 3. Quartile
Energy use [PJ]
Average COP [-]
Maximum heat pump supply temperature [°C]
0
2
4
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12
14
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100
120
140
160
180
200
220
240
260
280
300
320
340
T_{Process}
T_{WH}
Sink
Source
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Heat pumps in the electrification of the Danish industry
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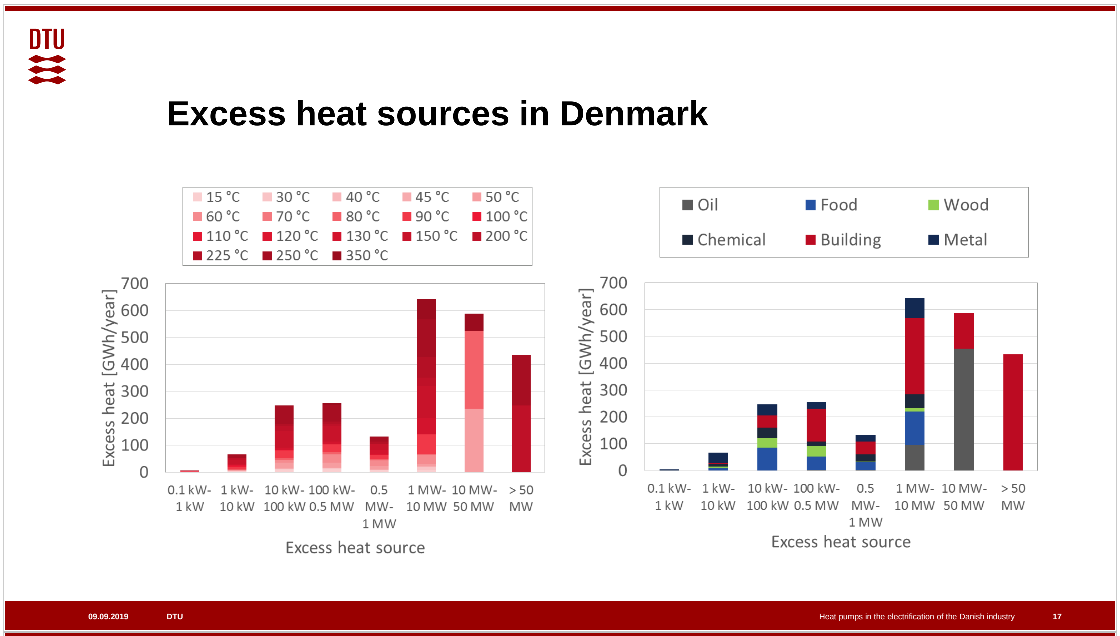
DTU
Excess heat sources in Denmark
15 °C 30 °C 40 °C 45 °C 50 °C
60 °C 70 °C 80 °C 90 °C 100 °C
110 °C 120 °C 130 °C 150 °C 200 °C
225 °C 250 °C 350 °C
Excess heat [GWh/year]
0.1 kW-1 kW 1 kW-10 kW 10 kW-100 kW 100 kW-0.5 MW 0.5 MW-1 MW 1 MW-10 MW 10 MW-50 MW > 50 MW
Excess heat source
Oil Food Wood
Chemical Building Metal
Excess heat [GWh/year]
Excess heat source
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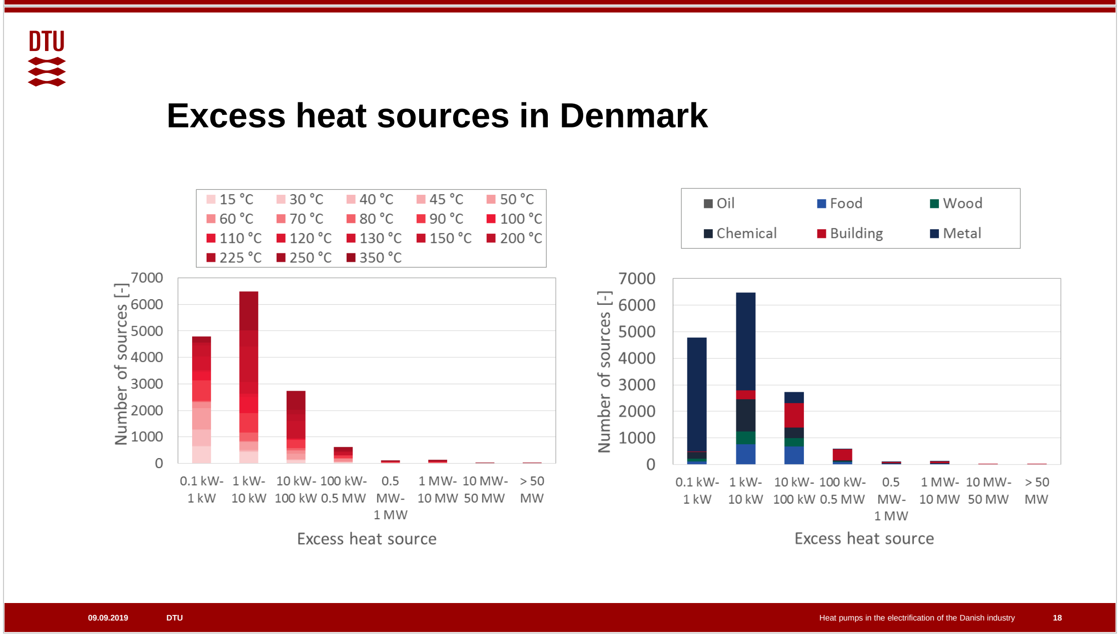
DTU
Excess heat sources in Denmark
15 °C 30 °C 40 °C 45 °C 50 °C
60 °C 70 °C 80 °C 90 °C 100 °C
110 °C 120 °C 130 °C 150 °C 200 °C
225 °C 250 °C 350 °C
Number of sources [-]
0.1 kW-1 kW 1 kW-10 kW 10 kW-100 kW 100 kW-0.5 MW 0.5 MW-1 MW 1 MW-10 MW 10 MW-50 MW > 50 MW
Excess heat source
Oil Food Wood
Chemical Building Metal
Number of sources [-]
Excess heat source
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Concluding remarks

- Electrification through heat pump integration
  - Reduction in final energy use and energy related operating costs
  - ELIDI project will demonstrate feasibility for other case studies
- Denmark with high amount of low temperature heating demand
  - High electrification potential with existing technologies
  - Reduction in final energy use
- Excess heat utilization for process heating in Denmark with heat pumps
  - Majority of excess heat useable for process heat up to 150 °C
  - High number of very small excess heat sources
  - Recovery potential in food and non-metal minerals between 1 and 10 MW

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Thank you for your attention!

Fabian Bühler
Technical University of Denmark
fabuhl@mek.dtu.dk
+45 22471020

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MEMO

Project: 1775 – Elforsk – Elektrificering

Subject: ELIDI – Bottlenecks for electrification

Date: 2020.11.03

To: ELFORSK and ELIDI, DTU

Copy to: Fridolin Müller Holm, Viegand Maagoe

From: Morten Sandstrøm Petersen, Viegand Maagoe

Table of Contents

1 Summary of the baseline for electrification

The present memo presents thoughts on general bottleneck issues that might arise for both private companies and on societal level in the transition to an electrified industrial sector and society in general. The memo has its roots in the Danish energy - and industrial sector and does not include bottlenecks within transportation, as the memo mainly focus on the manufacturing part of the industrial sector for Scope 1 and 2. [1]

It is widely evident that the only way to reach thorough decarbonisation of the global society, is to make extensive investments in replacing fossil fuels with renewable energy sources such as solar PV, wind power, biomass etc. [2]

During time, the investments in renewable energy sources in combination with successful energy storage will rule out the fossil fuel combustion for electricity production to the grids and thus decrease the emission factors.

Also, the emission factor of the gas mix in the gas grids will slowly decrease, which is shown in the predicted development of the Danish Energy Agency from 2020, where the emission factor of pipeline gas is expected to decrease from 178,2 kg CO_2 / MWh in 2020 to 149,0 kg CO_2 / MWh in 2030 as more biomethane is added to the mixture. [3]

The emission factor for electricity in the Danish grid is expected to decrease from 111 kg CO_2 / MWh in 2020 to 12 kg CO_2 / MWh in 2030, based on the method of the Danish Environmental declarations.

The emission factor for district heating in the Danish district heating networks is expected to decrease from 59 kg CO_2 / MWh in 2020 to 32 kg CO_2 / MWh in 2030.

From the emission factors above, it is evident that the emissions from general household will decrease as the electricity – and district heating use will emit less CO_2 in combination with the new Danish governmental agreement of phasing out natural gas – and oil boilers in common households, which will decrease the CO_2 emissions even further. [4]

The implementation of electric technologies not only offers CO_2 emission reductions from the difference in emissions factors, it also provides CO_2 emission reduction from energy savings, as electric technologies tend to reduce losses and increase the energy efficiency.

However, the phasing out of household oil boilers and the decreasing emission factors of the various grids will only have a narrow positive effect on the industrial sector in Denmark, as the far largest part of the industrial sector supports its processes by the combustion of fossil fuels and especially natural gas.

This is also presented in Figure 1.

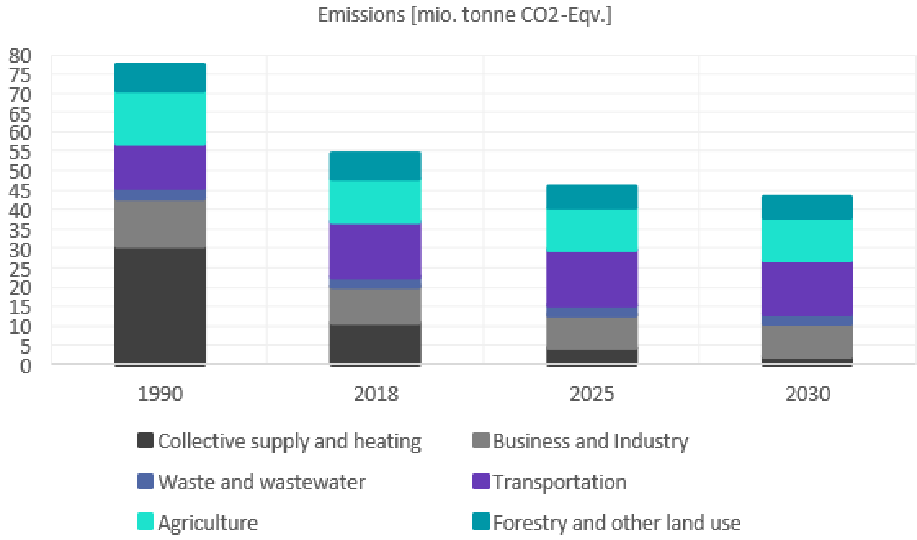

Figure 1 Development of the CO2 emissions from various Danish sectors. [5]

From the figure above it is shown that the CO_2 emissions from collective supple and - heating in dark grey are to decrease to a minimum in 2030, whereas the CO_2 emissions from the production industry are expected to be almost constant from 2018 and towards 2030.

In 2019, the Danish industrial manufacturing sector consumed a total of 43.745 TJ from fossil fuels of which 26.896 TJ consisted of natural gas. The natural gas combustion from the industrial manufacturing sector is equal to approximately 24,0 % of the total natural gas combustion in all of Denmark, found from the national energy balance for 2019.

This work especially focuses on the manufacturing industry, as the manufacturing industry makes use of all sorts of technologies and processes to prepare their goods, why the foundation for electrification is large. Many of the findings from bottlenecks associated with electrification in the manufacturing industry is comparable to other sectors such as transportation, service, agriculture, etc.

2 Bottlenecks associated with electrification

From the latter, it is found that measures should be made towards electrification, and even to introduce biogas for combustion where particularly high temperatures are needed in such way that electrification is not an option, to reduce the emissions from the industrial sector.

There are however various bottlenecks and barriers for electrification which are to be mitigated to obtain the highest level of electrification possible, as overall electrification barriers are a reality both to private companies and on a national level.

Specific bottlenecks for electrification are not common to private companies and global society, they are however based on the same overall subjects such as technical -, political/organisational -, economical - and risk-based bottlenecks.

For private companies, the incentive to invest is often limited by internal organisational conservatism and economy, as no development towards electrification and renewable based production facilities can be expected, unless the business case meets the organisational success criteria for profitability. However, the success criteria might become more fluent in the future, as other aspects have become important regarding feasibility of projects including investments in electric technologies. Electric technologies offer energy savings and thus emission reduction, whereby the companies broaden their foundation for sustainable branding. Moreover, investing in electric technologies is diligence, as the future might involve legislation on CO_2 emission fees, that might increase the marginal cost of energy consumption and therefore the international competitiveness.

Several movements both on legislative level such as decarbonisation goals towards 2030 and 2050 and consumer movements towards brands based on renewable manufacturing processes might affect the transition to electrification. Electrification can effectively aid companies in meeting the decarbonisation goals and renewable production might increase the cashflow from final goods compared to baseline.

For the government and general society, the incentive to invest is based on whether electrification is socially profitable concerning e.g., risks of impaired security – and quality of supply and whether the electrification promotes the competitiveness which generates increased societal wealth. However, many countries have agreed on following the Paris Agreement, why electrification should also be a tool towards meeting the common responsibility of decreasing the Green House Gas emissions.

In the following sections, some of the overall bottlenecks and barriers for electrification specific to private companies and on national level are presented, to sum up the overall challenges, society comes across and should be aware of in the future of electrifying.

3 Company specific bottlenecks

In Figure 2, a gross overview of electrification bottlenecks is presented for 4 main subjects within electrification barriers in companies: Economic -, Organisational -, Technical - and Risk based bottlenecks.

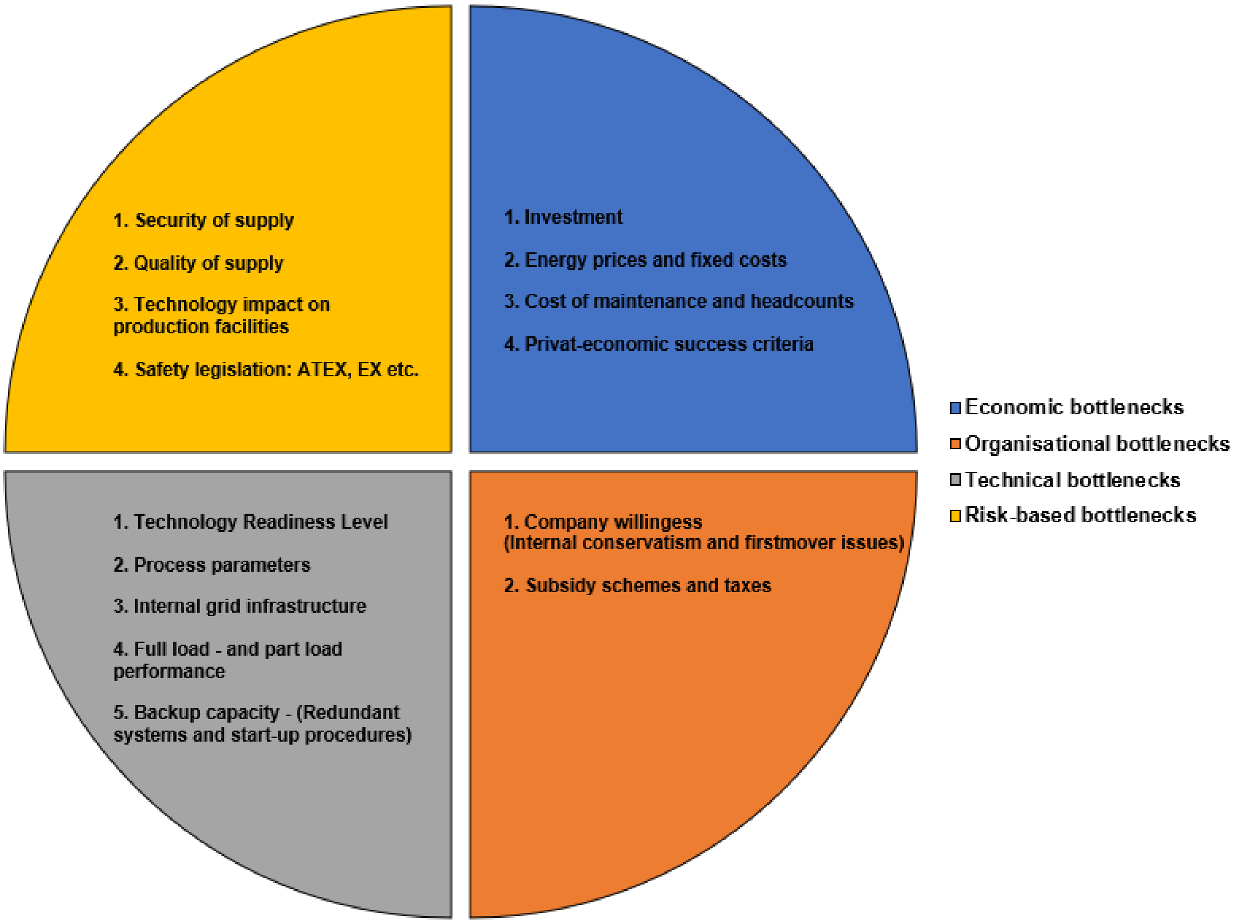

Figure 2 Bottlenecks for companies facing electrification.

3.1 Risk based bottlenecks

The risk-based bottlenecks, relevant to manufacturing companies, originate from production safety and concerns external factors such as security of supply, and internal factors such as technology impact on the product quality along with safety legislation such as ATEX.

3.1.1 Security of supply

Renewability of electrification solely depends on the sources of the grid such as solar PV, wind power, hydro power, nuclear power, etc., which also imposes requirements on the grid development towards neighbour countries due to import/export of electricity. However, one of the main challenges in operating renewable-based electricity grids, are the weather conditions, where cloudy and windless weather conditions entail low electricity production, why electricity should nationally be produced elsewhere from other sources or imported from international grid connections.

If the grid supplying power for electrified production facilities experiences a power failure, production facilities shut down which might be costly for companies with continuous manufacturing processes in terms of delayed production or disposal of ongoing batches.

However, in large parts of Europe and especially in Scandinavia the security of supply is very high, why supply-failures might not be frequent in the future. However, for countries of less well-developed grid infrastructure, the increased electrification for companies might meet challenges in power outages.

3.1.2 Quality of supply

As the electricity grids develop nationwide, severe focus should be put on maintaining and meet challenges on the quality of supply, as grid disturbances might have large negative effect on both the domestic - and larger consumers such as manufacturing sites etc.

There are mainly five categories of grid disturbances: Voltage unbalance, voltage interruptions, flicker, transients, and harmonic distortion as described in. [6]

All the five main categories mentioned above include several sub-categories of grid disturbance factors, all of which could affect grid and end user in a different manor. Most severe are the types of disturbance that affect the end user's data processing equipment which could ultimately become problematic to secure stabile manufacturing processes.

3.1.3 Technology impact on production facilities

For manufacturing companies, recipes for either medicine, food products, etc. are very precise and in many cases approved for ingestion on an international scale, which might be approved also based on the technology of manufacturing, being i.e., baking, spray drying, boiling etc.

Some technologies within the manufacturing industry are replaceable by other electricity-based technologies without having negative impact on the quality of the final goods. Some replacements might imply large amounts of documentation to secure the product quality etc., which ultimately increases the need for resources for the companies.

However, as time goes, some countries might put down deadlines for manufacturing companies to reach national goals on CO_2 emission reduction. The deadlines for reducing emissions could be accelerated by the imposing of CO_2 taxes which increases the marginal cost of production. Some industries might be forced to invest in technologies that are not entirely fulfilling from a manufacturing point of view due to Technology Readiness Level, (TRL).

As compromising the product quality is rarely an option for the companies, the companies could potentially move their production to locations in other countries where legislation on fossil fuel combustion is not yet rearranged towards improving the integration of electric technologies.

3.1.4 Safety legislation: ATEX, EX etc.

When companies are electrified to a larger extent, both national and international legislation regarding electricity devices and electricity intensive companies might become even more relevant than under current conditions.

As an example, many companies have processes concerning ATEX and the risk of fire or explosion hazards due to electrical equipment in combination with dusty atmospheres or atmospheres rich on e.g., alcohol within the production facilities.

As a larger amount of electric equipment is integrated into the production facilities, there is a greater risk of static electricity or general spark formation, why process equipment must be approved for production in these types of environment.

The increased extent of legislation within manufacturing with increased installed electric capacity, might be costly for the manufacturing sites, as components of ATEX approvement are more expensive than similar components without ATEX approvement.

As the environmental aspect of the electrification is decarbonisation, the correct use of refrigerants is important as some refrigerants have a large Global Warming Potential, GWP, compared to CO_2.

As heat pumps are expected to be a significant part of the future heat supply in the industry, refrigerant legislation should be complied with in terms of safety precautions including ventilation and evacuation plans etc. Considering e.g., Ammonia as the refrigerant of choice, which is a natural refrigerant with a GWP of 0, several safety precautions should be made due to the flammable and poisonous nature of Ammonia.

An Ammonia leakage is a possibility in the event of a crash or failure. According to European and Danish legislation, (EN 378), the power to the machinery room needs to be cut of if a high-level Ammonia alert is occurring. Because of the latter, all heat pump units must be shut down, if they are placed in the same building. This would lead to production shut down.

To prevent that an ammonia leakage could shut down the entire production, heat pump units could be placed into smaller groups in separate buildings, which should all comply with the legislation on Ammonia as a refrigerant. This will increase the capital investment cost for the electrification project of such kind.

3.2 Economical bottlenecks

In the following sections, company specific economical bottlenecks for electrification are presented. Overall, there are both CAPEX reasons and OPEX reasons that electrification might be costly for manufacturing companies compared to baseline conditions, however, in many cases there are just as many reasons for the opposite positive to the economy of the companies.

3.2.1 Investment

Many companies have old production facilities based on combustion of fossil fuels to supplement their processes. As companies are to integrate electric technologies as local hot utility from electric boilers, direct integration of new technologies in the processes as e.g., Mechanical Vapour Re-compression, (MVR), or centralised electric utility production such as large-scale heat pump systems or electric steam generators, the companies might experience elevated capital investment costs, as the electric technologies might be more costly compared to classic original ones based on fossil fuels.

The reason of such, is that technologies based on fossil fuels have been developed and refined through a significantly longer period than new electric technologies.

An example of this, is that High Temperature Heat Pumps, (HTHP), exists, but operates at low - medium efficiency and at low - medium capacities, compared to e.g., natural gas boilers for steam generation. Simply, there has been no incentive to research within the field of HTHP to supply heating at elevated temperatures, as the relevance of electrification is rather novel. Large scale steam generation from fossil fuel combustion started on an industrial scale around 1867. [7]

In comparison, heating by heat pumps first started to become somewhat competitive around 1950. [8]

Heat pumps might not reach temperatures alike those of fossil fuel combustion, but as a large part of the temperature levels within the manufacturing industry is below 200 °C, where heat pumps eventually could be relevant. However, as companies chose to invest in HTHP, they invest in technology development, and not in a technology that is already firmly anchored to almost all parts of the manufacturing industry, which might be a source of uncertainty to the companies.

Finally, the return of investment in electric technologies is highly volatile to the cost ratio of electricity and fossil fuels that could potentially experience large variations from external factors such as taxes, war, natural disasters, change of governments etc.

3.2.2 Energy prices and fixed costs

Another bottleneck for electrification, and one of the most important ones along with the capital investment cost, is the cost of electricity and especially the cost difference between electricity and the baseline energy source e.g., natural gas.

The fixed cost of electricity will affect the variable cost of the electrified system and will, if very high, be harmful to the overall business case of electrification of a certain process or an entire manufacturing site.

From Figure 3, it is presented how the electricity - and natural gas prices on a spot level for consumers are expected to develop towards 2030 along with the energy price ratio.

It is found that the cost ratio between e.g., electricity and natural gas is significantly important when evaluating the business case in electrifying.

The trend from Figure 3 shows that the cost of electricity is expected to be higher than that of natural gas at least for the next 10 years to come for consumers of both primary energy sources. Earlier, the ratio between electricity and natural gas was far higher than estimated today, but as it is still above 2 and upwards of 2,4 in 2024, electric technologies should either save large amounts of energy or have an efficiency higher than 240 % to indicate a break-even status of the yearly expenditures for energy consumption, and even higher to indicate a profitable business case of electrification.

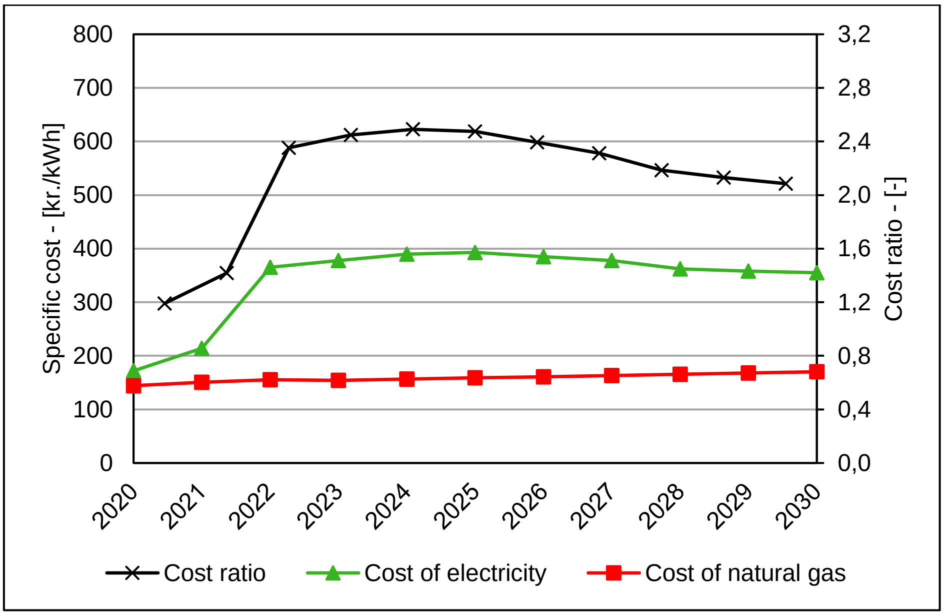

Figure 3 Expected development of cost of electricity and natural gas in Denmark. [9]

From the ratio above, especially heat pumps are interesting, and experience from implementation of electrically heated technologies shows that such technologies might save significant amounts of energy at advantageous energy efficiency, as various losses from the combustion process, exhaust gasses, and the transmission loss of e.g., are excluded.

Another parameter, important to include in the overall feasibility of electrification projects, is whether the company of interest is labelled in the EU ETS (European Emission Trading System).

Being involved in the European Emission Trading System, (ETS), companies of particularly high emissions are granted a certain amount of quotas for free, and emissions beyond the number of free quotas are traded at a still increasingly high cost. [10]

Moreover, the amount of free quotas decreases in the future, why companies are forced to pay for more quotas at an increasingly cost, which increases the marginal cost of fossil fuel consumption which underlines the relevance of electrification.

To involve the cost of quotas in the cost of e.g., the total cost of quotas is divided on the total amount of consumed natural gas, whereby the marginal cost of natural gas increases.

2020 numbers indicate that the cost of CO_2 quotas was approximately 261 DKK/ton [11], which ultimately results in the combined cost of natural gas for ETS companies to be around 10 % higher than non-ETS companies.

By looking at the expected development of CO_2 quotas from [9], the projection indicates an increment of the quota cost of 30 % in 2030 compared to 2020.

From this, when the marginal cost of natural gas and other fossil fuels is higher for companies that are registered in the ETS, electrification in these companies might be more profitable compared to companies that are not, as the marginal savings from energy consumption are higher. It should be noted that

Viegand Maagøe

the specific cost of emission quotas is volatile to the market development and might be difficult to fully predict, why the impact of quotas might be larger than presented above, which increases the incentive for electrification further.

3.2.3 Cost of maintenance and headcounts

New electric technologies either for central utility systems such as steam - or hot water generation or for direct integration in the manufacturing processes is to some extent expected to increase the yearly expenses for maintenance.

Considering a central heat pump system for process water heating to 85 °C that replaces a system consisting of a natural gas boiler, the unintended event of a heat pump stop is far more likely than a stop in the existing boiler unit.

In general, an investment in e.g., a heat pump, the project leads to a facility with a much higher number of “moving parts” than before implementation of the heat pump. Moving parts are simply more likely to fail than non-moving parts that are not represented in large numbers in a classic boiler setup. If the central steam generation system is replaced by an electric boiler, no change in expenses for maintenance is expected.

Even though heat pumps supplying heat at up to 90 °C is a mature technology, they are a machinery that can fail. If the possibility of a heat pump outage exists, risk mitigation measures should be made. The heat pump system could consist of several heat pump units, resulting in a redundant system of n + 1 or even more, where it is not likely that more than one unit will crash at the same time. By having a redundant system, an efficient maintenance protocol can be followed to secure an even amount of running hours of the heat pumps to apply equal amounts of wear and tear.

To avoid break down of the system, the company might have increased expenditures from maintenance of the heat pump system both from internal employees and external technicians, compared to the original boiler system.

The latter can be challenging for companies with low economic leeway for increasing the number of headcounts or expenditures in general, as it can be expected that increased electrification increase the demand for hiring employees with the appropriate technical knowledge or external consultants.

Some redistribution of technicians from the original technologies might be possible, but it is not expected that current technicians have the same knowledge of new electric technologies.

3.2.4 Private-economic success criteria

Common to most companies, investing in new technologies only takes place if the business case is profitable or unless the company is imposed the investment due to legislation.

Common to most companies is that they have an internal and thus private-economic success criteria based on Simple Payback Time, (SPT), Net Present Value, (NPV), or Internal rate of Return, (IRR). Many companies make use of the SPT to quickly evaluate whether an investment is worth undertaking or if the SPT is larger than their frame of reference, e.g., 3 years.

During recent years, it has become more common for companies to assess day-to-day investment projects using NPV, which evaluates the economic potential of the investment, e.g., over the course of the lifetime of the investment.

The first method of assessing an investment, the SPT, could be somewhat harmful to a large part of electrification projects, as the projects are of a significant capital investment, why the business case might seem unprofitable during the first 3 – 5 years.

However, if the latter method of assessing the investment based on NPV is used, the outcome of the business case is expected to appear different. This is caused by an expected lifetime of electrification technologies of at least 15 years if maintenance is performed regularly according to the supplier's regulations.

During the lifetime of the investment, a discounted cash flow accumulates which is affected by general energy savings, decreasing energy cost ratio between electricity and fossil fuels, increasing cost of CO_2 quotas, etc. In other words, the profitability of investing in electrical technologies is expected to increase in the future, as several factors that affect the profitability positively become more significant.

From this, the companies should re-evaluate their internal success criteria, so that in the future a SPT of projects could accepted at higher levels e.g., 7 years, or that investments are evaluated using NPV to a larger extent.

Accepting higher SPTs and lower NPV might be a necessity, if the company in focus has an ambitious climate strategy to reach certain sustainability goals in e.g., 2030. Therefore, a novel success criterion could be to focus on the marginal cost of CO_2 emission reduction compared to running the manufacturing equipment based on traditional fossil fuel combustion.

Finally, accepting an investment with SPT's at higher levels for electric technologies could potentially increase the variable income from additional sales, as the demand for goods based on renewable energy sources and - commodities is increasing, why companies could potentially benefit from green marketing. [12]

3.3 Organisational bottlenecks

In the following section, bottlenecks for electrification from within the management organisation of companies are presented.

As earlier stated, many companies within the manufacturing industry have old utility systems and production lines that are inefficient and relevant to the transition to electrification, without the companies knowing that it most likely would increase the Key Performance Indicators, (KPI), on their products.

The days go on and so does the production as it has always done, and organisational conservatism might focus on utilising the company's resources to keep the production lines and the flow of goods running. This is caused by the fact that companies have a short sales pipeline, which makes it difficult to involve themselves in long term investments.

To successfully electrify the manufacturing industry, the concept of electrification should be communicated to the manufacturing industry even more and with such transparency on subsidy schemes and energy savings potential, that companies investigate the potential of electrification when old manufacturing devices are to be replaced by new equipment.

3.3.1 Company willingness

From the above, an essential bottleneck is the willingness of the companies to invest in electrification technologies even though it might be untouched ground for the company specifically.

Here, the Firstmover issue arises, as only few companies are interested in being the first to letting their processes rely on completely new production – or utility technologies, such as High-Temperature heat pumps for process heating. Companies are often dependent on references from other companies of investments in novel technologies before investing in the technologies themselves. Ultimately, some companies must invest to increase the foundation of references.

To create a wave of increased transition towards electrification, companies should be willing to trust the potential in energy savings and decarbonisation potential to be commensurate with the investment and that technical challenges after the project start-up are manageable without harming the final products.

The company willingness to invest should be promoted by enlightenment through publication of technical articles on research of similar projects, dialogue with supplies of electric technologies, sharing of knowledge between companies, media coverage, and governmental support.

3.3.2 Subsidy schemes and taxes

Economy is amongst the largest bottleneck for electrification, and opaque subsidy – and surcharge schemes result in uncertainty in the companies which could potentially narrow down the scope of their business cases, which results in the CAPEX relevant to the company to be higher than in fact true.

Increasing the transparency on support schemes and charges on energy sources and waste heat recovery would increase the companies' willingness to invest, if it is evident that a significant portion of the capital investment is covered by either national or international support schemes.

In Denmark, the Danish Energy Agency grants support for projects of energy savings and long lifetime, why many electrification projects would benefit from such scheme. [13]

The subsidy is assessed in such way that the scale of the subsidy increased for smaller companies, as presented below.

- Large company: Maximum 30 % coverage of the total capital investment

- Medium company: Maximum 40 % coverage of the total capital investment
- Small company: Maximum 50 % coverage of the total capital investment

Moreover, European funds such as the Innovation fund, (InnovFund), grant subsidies for projects of significant energy savings potential, where the technologies or general project solutions are innovative.

The fund offers subsidies for Small Scale Projects < 7,5 mio. EUR and for Large Scale Projects > 7,5 mio. EUR. The Innovation fund could thus be relevant to electrification projects with some degree of Firstmover potential and efficient energy utilisation. Such projects could be steam production using HTHPs to replace traditional steam generation from fossil fuel combustion or by the implementation of a large energy storage, either thermal or electric.

Moreover, the granting of subsidies also relies on whether the project of decreasing the energy consumption is scalable to other companies and parts of the industry, to enhance the sharing of knowledge between companies. [14]

Considering electrification projects, these are in the scope of becoming such scalable projects, as many of the electrification technologies are to some extent well known technologies, but when integrated with other processes in the industry, they become applicable in many sub-sectors of the manufacturing industry.

3.4 Technical bottlenecks

In the following section, technical bottlenecks for electrification are presented along with thoughts on how to assess technical issues and solutions for manufacturing processes.

An electrification solution often revolves around a complete change in the supply structure or the core process of a production facility.

Current facilities with a central steam generation plant that supplies steam to a steam distribution system, with all processes across the facility to be supplied from the steam distribution system, are by far the most common type of internal supply setup in the manufacturing industry, where a large part of it rely on heat demands of < 250 °C.

If a new factory were to be built, it would most likely rely on a central combustion unit.

Considering a producer of food products, the relevant Best Available Techniques (BAT) Reference Document for Food, Drink and Milk Industries section "*2.1.2 Energy consumption*" (KARLIS Panagiotis, 2019) states that:

"FDM manufacturing requires electrical and thermal energy for virtually every step of the process. Electricity is needed for lighting, for process control of the installation, for heating, for refrigeration and as the driving power for machinery. It is usually generated and supplied by utility companies. When steam and electricity are generated on site, the efficiency factor can be considerably higher.

Thermal energy is needed for heating processing lines and buildings. The heat generated by the combustion of fossil fuels is transferred to the consumers by means of heat transfer media, which, depending on the requirements, are steam, hot water, air or thermal oil." [15]

Moreover, BAT states that thermal energy is needed for heating of processing lines, which originates from combustion of fossil fuels. Furthermore, it is stated in section *"2.1.2.1.2 Heat pumps for heat recovery"* that *"Heat pumps are generally only a good solution when the site energy recovery has been fully optimized and only low-grade heat remains"*.

From the above stated, it is evident that electrification is not yet fully thought of as a BAT for process optimisation and deep decarbonisation within the manufacturing industry, and that the use of e.g., heat pumps as the main heat supplier for industrial processes at temperatures of upwards of 100 – 120 °C is not yet thought of as a possible utility system.

3.4.1 Technology Readiness Level

Some processes in the industry operate under such conditions that finding alternative technologies is challenging. A way of assessing these technologies is the Technology Readiness Level, (TRL), which defines how development level of certain technologies within various fields of the industry and for various capacity limitations such as temperature, pressure, etc. The TRL goes from 1 to 9, 1 being the fundamentals of a certain technology have been found, and 9 being the most developed proving an actual system in an operational environment. [16]

Although a technology has been fully developed for a specific application does not imply that the technology is 100 % applicable for other industrial applications. This is caused by many of the electrification applications to be either fully or partly custom made for a given industrial process at a certain manufacturing site.

Finally, a TRL of 9 does not necessarily imply that the application is commercially easily available, as the technology might only be offered by 1 retailer on the market that has narrow correspondence to the market relevant to the customer. Also, if technologies are only offered by few retailers, the capital investment could be higher compared to technologies of many retailers due to the nature of market monopoly.

To some extent, electrified technologies have TRL of around 8-9 and are commercially available. However, when the electrified technologies should be competitive at elevated temperatures compared to the cost ratio between electricity and fossil fuels, the TRL decrease as electric technologies at such high temperatures have efficiencies of around 1. Only HTHPs could supply heat at efficiencies above 100 %.

However not many high temperature heat pumps have been commercialised.

3.4.2 Process parameters

The process parameters specific to a certain manufacturing process is just as essential to the amount of electrification possibilities as the manufacturing process itself, why the process parameters are also highly relevant to the TRL of technologies that might be relevant.

Several process parameters, such as temperature, pressure, flow, humidity, etc., are under current industrial conditions already obtained by electrified systems, using pumps, fans, electric driven cooling systems etc.

However, temperature is to a large extent still fossil fuel dependent at elevated levels, as only few and more novel technologies are technically competitive to traditional technologies of process heating, however not economically.

As earlier stated, heat pumps have a large potential for providing process heating to media temperatures upwards of 85 °C whilst still being price competitive to the traditional heating processes, such as steam generated by natural gas combustion for use in heat exchangers around a manufacturing site. This is caused by more than half of the process heat demand in the industry to be below 80 °C, which is fully within state-of-the-art heat pumps for industrial use that can be operational optimized by integrating the heat pumps in the process for waste heat recovery. [17]

Temperatures above 80 °C – 90 °C are somewhat troublesome for electric technologies to be price competitive to traditional technologies, as high-temperature heat pumps for temperatures up to 150 °C are not technologically mature and fully commercialised, why process heating at mentioned temperatures must be provided by technologies with efficiencies just below 100 %. Hereby the technologies are not 1-1 price competitive to traditional technologies unless the implementation of the electric technology results in significant energy savings that compensates for the cost difference of electricity and fossil fuels.

Such process heating technologies could be: Electric boilers, Electrode boilers, Inductive heaters, etc.

3.4.3 Internal grid infrastructure

When companies to a larger extent rely on electricity, their internal electricity infrastructure should be prepared for such increase in capacity, which might to some companies be a bottleneck even when the business case of a project is found to be profitable.

It is expected that large manufacturing companies to some extent already have a well-developed electricity grid. But for some companies, the transition to solely – or partly rely on electricity might result in an increased capital investment in increased grid capacity, which is from experience, costly.

Increased electricity consumption and upgraded internal grid capacity for manufacturing companies also requires that the installation of electric components such as motors are properly installed with Variable Frequency Drives, (VFD), of low Total Harmonic Distortion current, (THDI), to avoid internal disturbance on the grid that might affect the data collection abilities of operation software or even the performance of critical production machinery. Negative distortion to the grid could, if severe, result in reduced quality of the final goods or shutdown of the process equipment.

3.4.4 Full load – and part load performance

In general, many utility systems and components in general, have a point of operation where the energy efficiency is at its maximum.

In many traditional thermal powered processes such as evaporation, distillation, boiling, drying etc., the heat input is steam, hot pressurized water or – oil from a central utility system, where the product medium to be heated, circulates on the secondary side of heat exchangers or in the mantle of product tanks. If the process of heating is to be slowed down, less heat transfer fluid flows to the heat exchangers, circulation pumps of the product media slow down using VFD's, or valves partly close to decrease flow.

From the latter, the load on central utility systems is only slightly affected, unless the process of decreased energy consumption is the main process at the site. If many processes slow - or shut down simultaneously, the efficiency of the traditional central utility system could be negatively affected. [18]

When investigating e.g., heat pumps as electrical heating utility for a manufacturing company at local points in the manufacturing process, the efficiency of the heat pump system is to a much larger extent dependent on the load of the system.

Depending on the type of compressor, load affects the compressor efficiency, as very low loads might be significantly more inefficient for e.g., screw compressors than for reciprocating compressors. However, common to all types of compressors is the electric motor, for which the efficiency is expected to start decreasing significantly, if the load decreases to around 25 %. In fact, electric motors might not be able to run lower than 25 %. [19]

The decrease in electric motor efficiency combined with the decrease in efficiency of the compressor at small loads lead to a decrease in COP, which might be harmful to the business case of implementing heat pumps as utility system at a manufacturing site.

The decrease in efficiency of heat pump systems at sudden small loads could be addressed by the implementation of buffer capacity matched to the load variations. In this case, heat pumps could shut down during large load variations and start up again at loads suitable for high performance operation.

Besides the part load challenges in utilising heat pumps as utility systems for process cooling and – heating, part load challenges are relevant to all electric manufacturing equipment based on electrical motors, as the efficiency of electric motors in general decrease with decreasing load. [20]

Manufacturing companies should therefore investigate the best performing electric equipment for their processes which might result in a higher capital investment, but lower total costs during the lifetime.

3.4.5 Backup capacity – Redundant systems and start-up procedures

Many manufacturing companies have, over the course of several years and in good faith, optimised their processes by the means of waste heat recovery and process integration. Examples are process water heating from the condensation of alcohol from distillation columns and condensation of vapour from traditional TVR evaporators. Other examples are distillation columns driven by the output from other distillations columns upstream, whereby the processes are highly integrated. The high degree of process integration at manufacturing sites, might increase the investment cost for electrification, as the processes should to a large extent be de-integrated.

Many electric driven technologies do not offer the opportunity of integrating waste heat to other parts of the processes downstream or upstream, as the electric technologies in most cases, do not result in waste heat, why processes up- or downstream should either be electrified too or supported by utility from elsewhere.

Furthermore, electric driven manufacturing technologies should be connected, if possible, to redundant utility systems such as local electric steam generators etc., if the electric technologies depend on a thermal input to operate. Another option for having redundant systems is to keep traditional utility systems at the manufacturing site to start operation if needed.

As manufacturing sites implement a larger share of electric driven, some challenges might arise in terms of factory start-up after holidays or maintenance, when utilising waste heat recovery and process integration in the form of heat pumps as main heat input.

To some companies, processes at the output of the factory could act as stable heat input for e.g. heat pumps to supply heating at the beginning of the processes at the factory. This is exemplified by the diagram in Figure 4.

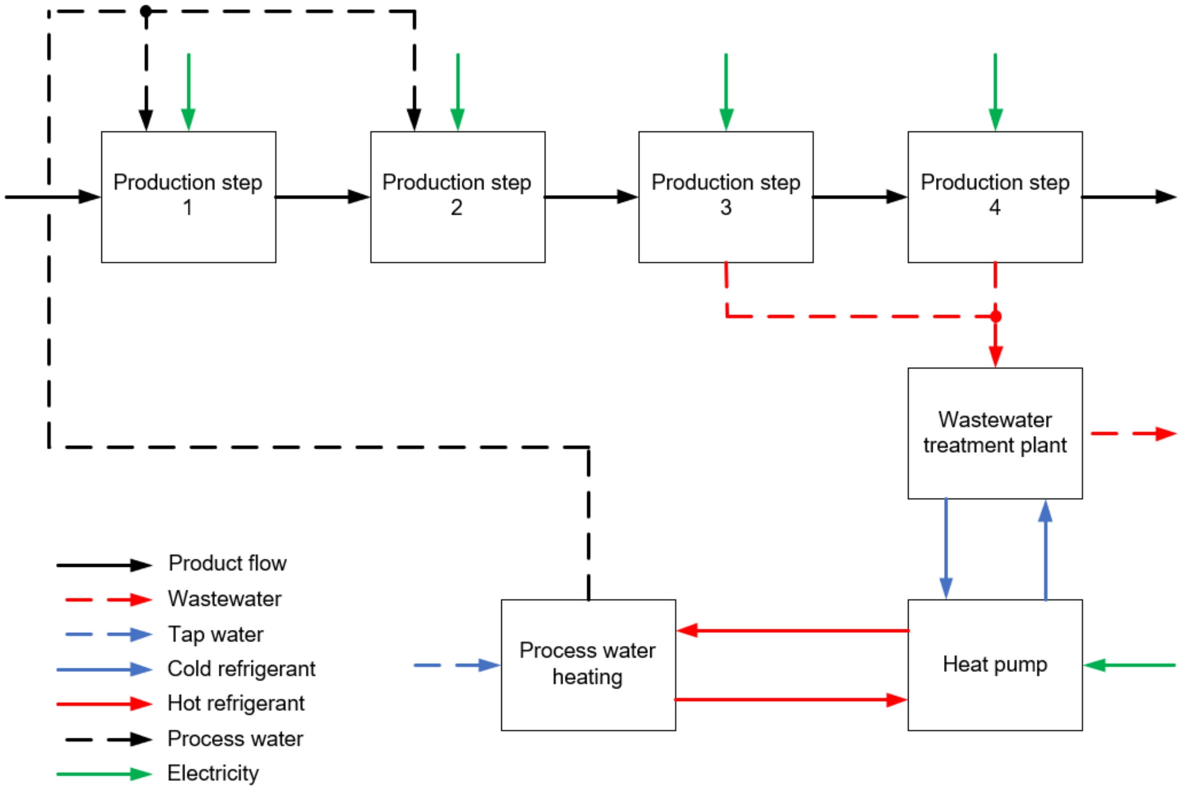

Figure 4 Example of an electrified process.

In the figure above, the process diagram represents an arbitrary manufacturing process of a certain product, based solely on electricity. The product flow starts from the far left and exits the production facilities on the far right. Hot process water is added in the first two steps of the overall process, and water is removed in the final two.

The water removed thus becomes hot wastewater.

The hot wastewater enters a wastewater treatment plant and before leaving the production site, the now treated and still warm wastewater act as heat input for an evaporator in a heat pump.

The evaporated refrigerant is compressed by a compressor and supplies heat for process water heating. The process water is then supplied to the first two steps of the overall process.

In a system like the one in the process diagram, issues during start-up might arise, as the overall process is highly dependent on hot process water, and the process water heating is highly dependent on the warm wastewater. When the production facilities have been shut down during holidays, during maintenance, or due to a power failure, no warm wastewater is available, why the heat pump has no heat input for hot process water production.

The issue might seem simple to solve, as a local heat input for the process water could be installed in terms of an electric boiler.

However, if many of such systems, where the heat input for the beginning of the processes is supplied by utilising the waste heat from the output of the final processes in the production chain, many backup systems should be implemented to secure continuous production which increases the capital investment, and internal resources should be allocated to prepare start-up procedures for the production facilities.

4 Societal bottlenecks

In the following, some bottlenecks for electrification are presented from a societal point of view. For the electrification of companies to have a significant and a positive impact on the decarbonisation, the electricity should be generated using renewable sources such as Wind, Solar PV, Hydropower etc. However, there are some challenges for the renewable power generation technologies and the national electricity grids that could potentially be a challenge for the electrification, as the power generation does not necessarily fit the consumption.

Also, the grid condition in neighbour countries could potentially be harmful to the expansion of renewable electricity sources if power cannot be supplied to the grid due to lack of grid capacity.

When national electricity grids evolve and smart grid technologies for electric vehicles and housing will affect the way of operating power grids in the future.

Also, the following briefly presents some health – and other issues relevant to the increasing amount of renewable power production facilities, which might affect the population and wildlife around them.

Peoples' opinions towards the risk of unintended health effects and optical disturbance from e.g., wind turbines at sea must be considered even if it seems to be an issue easily solved, as these obstructions from local society tends to postpone projects of installing renewable energy sources in areas with the possibility of unintended side effects.

4.1.1 Wind turbine noise pollution

Increasing electricity demand increases the demand for renewable electricity. To meet the demand, and not import or produce fossil fuel-based electricity when the weather conditions for wind turbines are ideal, due to scarcity of wind turbine installations, more wind turbines will be implemented both on land and at sea.

An increasing number of installed wind turbines does however pose a risk of noise – and visual pollution to citizens in countries of high density of wind turbines. The visual effects are disfigurement of the landscape, rotating shadows, and aircraft warning lights. The environmental impact depends on the proximity of the turbines to the neighbouring properties and how they are placed in the landscape.

The noise pollution is caused by mainly high frequency from the rotation of the blades, however also low frequency noise can be emitted from the turbines which is perceived as deep vibrating sounds. [21]

WHO suggests that the wind industry and policymakers should implement more suitable measures to mitigate the societal disruptions on wind turbine noise and visual pollution, as it may cause worldwide problems for citizens and wildlife. [22]

4.1.2 Investments

As the electrification increases on a societal scale, the need for increased grid investments increases too, even though the electrification leads to energy savings. There are various reasons of why the grid must be developed among which the following is particularly relevant, more RE, (Renewable Energy), production sites, increased private charging of electric vehicles, electrification of heavy transport and electricity consumption for heating purposes for private households and for district heating in large and dense communities. [23]

Such expansion of the power grid has high investment cost.

Fortunately, when assessing the Danish electricity grid, the expansion of the electricity grid along with the increase of electricity consumption on both a domestic and an industrial scale has been successful so far, as the security of supply is high, (above 99,9 %) [24].

However, in the future, the expansion can be expected to happen much faster due to more strict governmental demands towards reducing CO_2 emissions.

Therefore, traditional reinforcement of the national electricity grid should be supplemented by the integration of novel technological – and electricity market solutions, to supply the most efficient and stable electricity grid.

The high investment costs should however not harm the end-users in such scale, that the willingness is reduced.

Governments should provide the needed economic incentives that secure an optimised synergy between the end-users and the expansion of the electricity grid.

As the grid infrastructure, end-user demands and restrictions for carbon emission develops, investments in renewable electricity production facilities become more frequent. Historically, and still to some extent, the capital investment cost and OPEX of renewable energy systems are higher than those of traditional systems based on fossil fuels combustion.

High cost of renewable power production facilities could be a bottleneck, as the economic framework of such projects might not meet demands for socio economic success criteria.

However, in most recent years, the LCOE, (Levelized Cost of Electricity), has declined rapidly for the most common renewable sources, namely: Solar PV, Concentrating Solar PV, Onshore wind, and Offshore wind, as the effect of economy of scale has kicked in and reduced the manufacturing cost of such systems significantly. The development of LCOE is presented below.

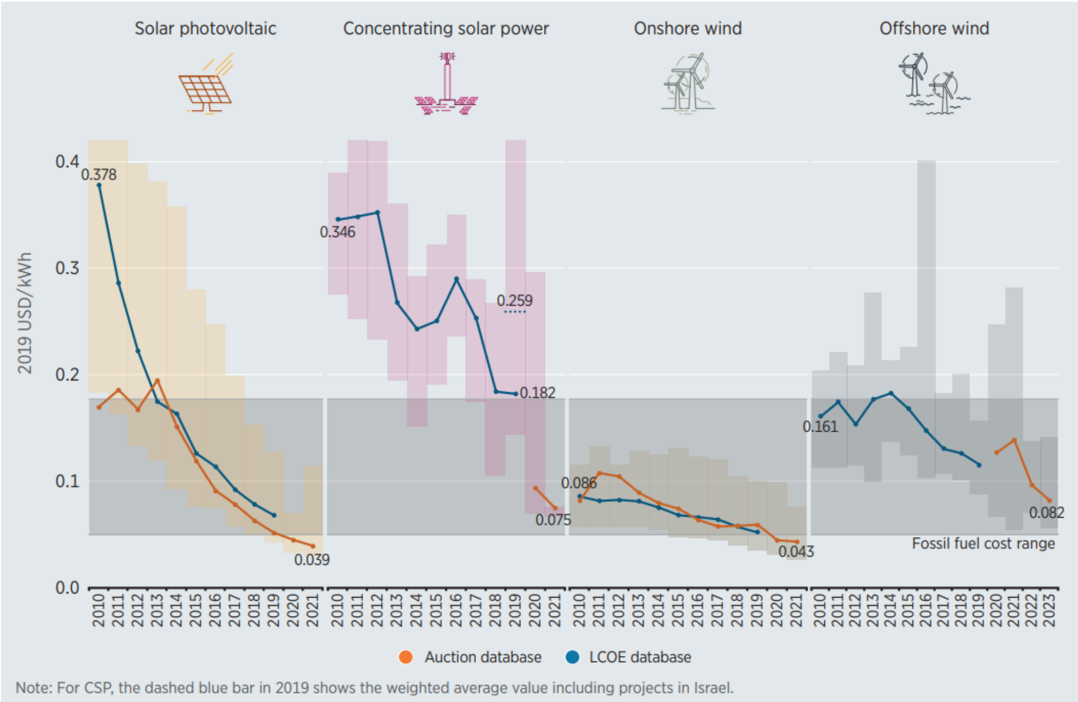

Figure 5 Global weighted average LCOE and Auction/PPA prices for CSP, onshore and offshore wind, and solar [25][1]

The main reason for the rapid decrease in LCOE of the renewable power production technologies is the increasing demand of such systems and therefore increased research and development within the field as well as greater competition between suppliers.

Therefore, the bottleneck of increased investment cost of renewable energy sources for increased de-carbonised electrification, might only become a real obstacle for countries with no tradition of relying on renewable energy sources and for countries where climate, geographic and topological factors make for difficult or impossible implementation of traditional technologies such as mentioned earlier. Here, other untraditional renewable energy sources might become relevant at increased investment cost to supply the power grid with renewably based electricity.

Also, connections towards neighbour countries with more advantageous conditions for renewable power generation could be a solution, as the neighbour country could the increase the manufacturing of renewable electricity systems from secured income from sales of electricity across borders.

4.1.3 Market energy prices

Market energy prices are affected by several factors depending on the geographical location of the grid in focus.

As an example, the prices of electricity in Scandinavia are highly dependent on prices of coal and CO_2 quotas and whether a specific year is defined as a dry – or a wet year.

The reason of the above, is because the electricity grid in Scandinavia is highly interconnected to the south of large amounts of coal combustion and to the north of large amounts of hydropower. If the coal and CO_2 quota prices increase, the cost of electricity does too, and if large amounts of precipitation take place in the north, the hydro power plants produce large amounts of electricity at lower cost.

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Less, but still somewhat determining for the cost of electricity in the north, is the capacity expansion on national scale and towards other countries. The investment costs will ultimately affect the cost of electricity for the end-users along with the import of electricity from countries with higher electricity prices, e.g., UK. [26]

Also, the investment cost of implementing redundant marginal plants such as coal, natural gas or biomass fired plants will affect the cost of electricity for the end-users. Therefore, the governments should strive towards the most economically beneficial market prices for the end-users, through socio-economically optimised investments to keep up the incentive to electrify.

It is however not only the increase in marginal cost of electricity that affects the incentive to electrify, as the real incentive is more affected by the cost ration between electricity and fossil fuels. Fortunately, the latter is decreasing in Scandinavia, as higher taxes have been imposed on the combustion of fossil fuels, and the renewable systems become more cost competitive.

4.1.4 Socio-economy

In private companies, investing in new technologies or in system optimisation via process integration to minimize the energy consumption and carbon footprint, will only occur if the capital investment is found to be feasible during the project assessment. In other words, increased income is always the driving force for investments in manufacturing companies, unless external restrictions are imposed such as carbon emission reduction goals or energy saving goals.

Like the private companies, if the capital investment costs are too high, nations might not invest as much in renewable energy sources towards green transition, as the high capital investment costs might displace financial resources for e.g., increased welfare within the health sector, elderly care etc., which might become a bottleneck for the implementation of large-scale electrification projects.

However, if the government chooses not to invest in renewable resources for electricity production, other consequences might decrease the socio-economy in terms of increased pollution from vehicles and fossil fuel combustion in power plants and at factories.

Therefore, investments in renewable sources for electricity production on a larger scale are a subject to certain socio-economic balances and – requirements. Following this, assessment of the socio-economic success in large scale utility projects is complex, time consuming and therefore expensive.

When it comes to the transition to a renewable powered future, there is however a larger scope than the risk of making investments that reduce the capability of increased municipal welfare in the following years, as the investment in green transition benefits the global society.

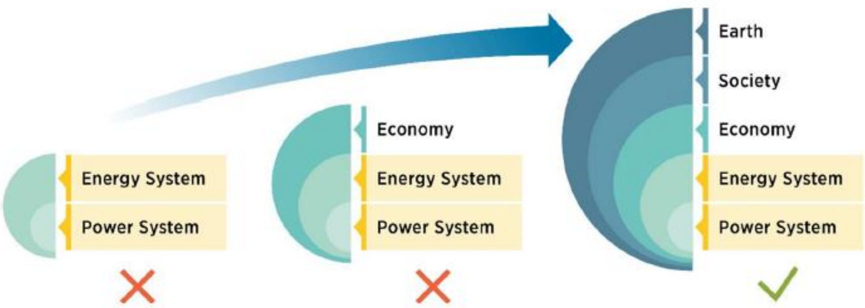

Figure 6 Power and energy systems as a part of a broader system. [25][2]

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There are several factors that should be included in the assessment of the socio-economy of large-scale electrification projects, as benefits such as: reduced GHG-emissions, reduced local pollution, reduced water usage, increased biodiversity, increased employment, increased GDP, increased economic structure and export, increased research and development, improved policy making, etc.

Although the benefits presented above are many, some countries are currently solely or to a large extent dependent on fossil fuel, why the transition to an electrified society might become overwhelmingly costly and challenging.

It is evident that such fossil fuel-dependent economies must include alignment of experiences from the fossil fuel sector to the incoming renewable energy sector and increase their economic diversification to increase their competitiveness and keep up the labour market during the transition.

4.1.5 Willingness and engagement

Historically, and the reason of the global environment to be at the current level of too high CO_2 content, politicians have focused on economic growth and welfare, and too little on the evolving climate changes and possible solutions to this challenge such as higher degree of global electrification, to supply renewable based energy for the expanding industrial sector and middle-class consumers.

Unless politicians manage to settle the frame for future transition to renewable powered industrial processes and domestic energy consumption in such way that it is economically beneficial for the companies and private consumers, the transition towards an electrified society will not succeed. Private consumers and the industry do not undertake a project of electrification, unless the capital investment is repaid within their acceptable time range from energy savings or unless the investment improves the product quality enough to increase the price of the final good etc. The electrification projects should simply allow the companies to maintain or improve their international competitiveness.

The political movement should be towards increasing the expenses for operating old and fossil fuel powered industrial – and domestic installations and to decrease the capital investment of electric powered solutions through the granting of subsidies both for investments and for research and development.

Moreover, politicians should increase governmental funding of research and development within the field of electric powered technologies such as high temperature heat pumps that are price competitive to traditional technologies such as natural gas boilers.

Legislation to enhance the common mindset towards a green transition should be combined with increased job creation in combination with increased welfare. In e.g., the European Union, the legislation should ideally be common across borders, to diminish the tendency of companies to switch location to other parts of Europe with more advantageous legislation on fossil fuel combustion.

4.1.6 Subsidy schemes and taxes

In continuation of the above, some countries in the EU did not reduce their CO_2 emissions in 2019 and some reduced only small amounts, as some countries are still very much dependent on fossil fuels as they do not have the same penetration of renewable energy sources in their power grid. [27]

In EU, at the time of writing, there are both subsidies for increasing of energy efficiency and for the opposite, fossil fuels. In some Member States in the EU, the energy efficiency subsidies have increased significantly over the last years, however, for many Member States also the subsidies for fossil fuels have increased which adversely impact the attainment of cilamate neutrality and transition to renewable based electricity in the power grid and industrial manufacturing processes. [28]

Viegand Maagøe

Subsidy schemes and surcharges for the combustion of fossil fuels should be concretized as well as electric powered technologies should be accommodated, so that countries of high penetration of renewables continues to develop grid infrastructure based on renewables, and that countries of lower penetration of renewable sources develop their power grids to cope with the technical challenges. The latter in combination with targeted subsidy schemes for the industrial sector and the domestic households to switch to electric powered technologies, could increase both the country welfare and the several parts of the "Technology Readiness Level" - spectrum.

4.1.7 Characteristics from renewable sources

The inertia of a power system is defined as the ability of a system to oppose changes in frequency, by utilizing the kinetic energy of rotating masses in individual turbine-generators in the system, which might become a bottleneck in the future of power systems, as increased amounts of renewable electricity production facilities offer low or no inertia at all.

The increasing share of Wind, Solar PV, and Hydro Power and more HVDC, (High Voltage Direct Current), connections, results in the total electricity system inertia to decrease, as wind turbines, solar PV and hydropower does not, or only to a small extent, contribute to the system inertia compared to traditional power plants.

This is caused by the fact that solar PV and Wind turbines are connected indirectly to the grid via power converters, why the rotating mass of e.g., the wind turbines do not deliver power at the grid frequency through the generator in the event of a sudden frequency decrease in the grid. [29]

Inertial response from modern wind turbines may be obtained through the utilization of synthetic inertia, that will apply electrical torque on the rotor of the wind turbine and thus extract kinetic energy from the turbine.

Inertial response from hydropower can be supplied somewhat more successful, however limited by the water levels in reservoirs and the flow in running river systems.

From solar PV systems, no system inertia is added as no rotating mass is present.

In power systems with high density of wind power, the need for reserves increase to secure a foundation for frequency balancing in the event of tripping. It was found by [30] that a 10 % wind power penetration in Scandinavian countries will increase the power reserve requirement by 1,5 % - 4,0 %, which will be costly to implement.

Moreover, for increased solar PV penetration in the power systems, increased events of overvoltage spikes might occur, which could lead to both tripping of power generation systems and production facilities at manufacturing sites etc.

4.1.8 National safety of supply

In an electrified society, greater demands on security - and quality of supply are placed on the TSO's and the power production facilities, as the economical foundation for end-users such as manufacturing companies rely more on electricity than ever before.

During the recent years, large parts of the European Network of Transmission System Operators, (ENTSO-E), have experienced increasing frequency variations and - amplitude for several hours during the common ramping periods in the morning and in the evening.

The deterministic frequency deviations have been found to be:

1. The link between power consumption from end-users and power generation has been weakened, as the existing market rules are outdated. Current rules do not follow more dynamic behaviour of the electricity system, as the current rules are based on energy blocks of fixed periods of time.
2. The current hourly transit period which generation schedules is based upon, is not defined between all market participants, why imbalances between consumption and generation are reflected in the frequency deviations. [31]

As electricity demand will increase from electrification and the common ramping periods could potentially be prolonged or even divided into more periods, frequency deviations could occur even more than under current conditions, which could ultimately cause disturbances for the end-users, causing e.g., manufacturing sites to experience production outage.

4.1.9 Connections across borders

The electricity market should always be in balance concerning supply and demand. However as the capacity of renewable energy increases in the electricity grid, periods of higher supply than demand become more frequent, why poor interconnection capacity towards neighbour countries could become a bottleneck for electrification using electricity generated by renewables.

As the frequency of periods of too high supply capacity increases in the future, the periods of negative spot prices for electricity increases too, which generates economical losses the stakeholders of renewable energy sources, and ultimately reduces the incentive to invest in renewable energy sources for future stakeholders.

By improving connections to nearby countries, the increasing frequency of negative spot prices on electricity can be reduced and more renewable electricity can be consumed in other countries thus displacing electricity generated by the combustion of fossil fuel.

In some cases, the improvement of cross border connections is challenged by the national electricity grid in the neighbour countries. Such scenario is present in the link between Denmark and Germany, as the northern part of Germany has a large-scale production of renewable electricity already, and the national link between the northern part – and the southern part of Germany has reached its capacity limits.

The heavy industrial societies in the southern part of Germany, still to a large extent rely on the combustion of fossil fuel, why an improved connection to the northern part of Germany could displace large amounts of CO_2 emission via electrification and general electricity consumption at the industrial sites.

The improved link in Germany would benefit the Danish grid electricity too, as more renewable electricity could be utilised in the increasing amounts of peak production periods, thus securing more hours of emissions free electricity consumption and increased sales.

Under current conditions, the Danish market must resort to special regulation, where Danish wind turbines disconnects from the grid in return of economical compensation from German generated by receiving German electricity. This ultimately means a waste in renewable electricity potential in Denmark and increased expenditures for the German electricity market.

Another indirect consequence of the special regulation is that consumers in the Danish electricity grid is economically supported by increasing their electricity consumption by the means of either negative prices of electricity or by zero payment.

The increment of electricity consumption for a specific consumer can be exemplified by turning on an electric steam generator and shutting down a natural gas fired one.

In the figure below, the active number of hours and the total activated amount of electricity displacement is presented for the Danish electricity market.

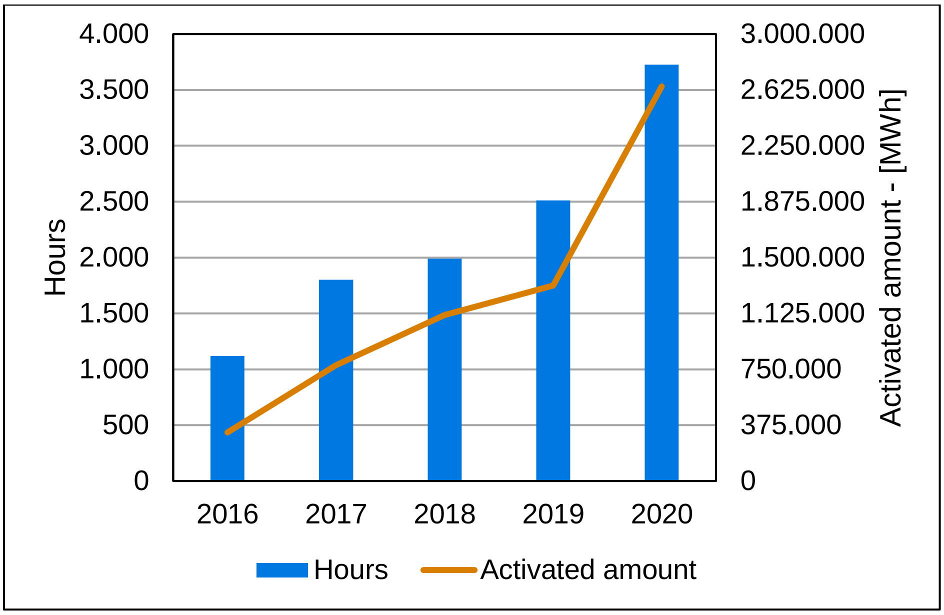


Figure 7 Development in special regulation of the Danish electricity grid.

The figure shows that the frequency of the special regulation to kick in is rapidly increasing as more power from wind turbines and other renewable sources is installed, and that the amount of electricity displaced by taking wind turbines out of operation is also increasing.

In 2020, around 2,6 TWh of electricity was displaced by special regulation, of which 48 % was obtained by shutting down Danish wind turbines and instead receiving electricity through the link to northern Germany. [32]

Viegand Maagøe

5 References

[1] "https://www.carbontrust.com/resources/briefing-what-are-scope-3-emissions," [Online].

[2] F. Bühler, F. Müller Holm and B. Elmegaard, "Potentials for the electrification of industrial processes in Denmark," Proceedings of ECOS, 2019.

[3] Energistyrelsen, "Basisfremskrivning 2020, Klima- og energifremskrivning from til 2030 under fravær af nye tiltag," Energistyrelsen, 2020.

[4] "https://kefm.dk/Media/2/3/Aftaletekst%20om%20tilskudspuljer%20og%20underst%C3%B8ttende%20tiltag%20-%20varme.pdf," [Online].

[5] "https://ens.dk/service/fremskrivninger-analyser-modeller/basisfremskrivninger," [Online].

[6] E. Hossain, M. Rida Tur and P. Sanjeevikumar, "Analysis and Mitigation of Power Quality Issues in Renewable Energy Based Distributed Generation Systems Using Custom Power Devices," *IEEE Access,* 2018.

[7] "https://insulation.org/io/articles/the-history-of-the-steam-generating-boiler-and-industry/," [Online].

[8] "https://www.ehpa.org/fileadmin/red/03._Media/03.02_Studies_and_reports/History_of_Heat_Pumps.pdf," [Online].

[9] Energistyrelsen, "Fremskrivning af brændselspriser og CO2-kvotepris," Energistyrelsen, 2019.

[10] "https://www.retsinformation.dk/eli/lta/2016/1605," [Online].

[11] "https://www.theice.com/products/197/EUA-Futures/data," [Online].

[12] B. Baker, J. Deborah and L. Bird, "Made with Renewable Energy: How and Why Companies are Labeling Consumer Products," NATIONAL RENEWABLE ENERGY LABORATORY, Colorado, 2012.

[13] "https://ens.dk/ansvarsomraader/energibesparelser/virksomheder/erhvervstilskud-til-energieffektiviseringer," [Online].

[14] "https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/innovfund/wp-call/call-fiche_innovfund-lsc-2020-two-stage_en.pdf," [Online].

[15] P. Karlis and S.K., "Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries," Publications Office of the European Union, 2019.

[16] M. E. Mondejar, J. Kjær Jensen and B. Elmegaard, "Elektrificaering af Fødevareindustrien," 2020.

[17] C. Arpagaus, F. Bless, M. Uhlmann, J. Schiffmann and S. S. Bertsch, "High temperature heat pumps: market overview, state-of-the-art, research status, refrigerants, and application potentials.," Energy, 2018.

[18] A. Kumar, A. Arya and R. Kumar Singh, "Variation of boiler efficiency with respect to boiler loads by increasing of excess air," International Journal of Engineering Research and Science & Technology, 2014.

[19] "https://www.rehva.eu/rehva-journal/chapter/capacity-control-of-heat-pumps," [Online].

[20] "https://na.eventscloud.com/file_uploads/68ca8b17f0f403bd435fca1b0efec269_T7_MotorManagementVeryGood10097517.pdf," [Online].

[21] "https://eng.mst.dk/air-noise-waste/noise/wind-turbines/," [Online].

[22] "https://www.masterresource.org/wind-turbine-noise-issues/wto-wind-turbine-noise-as-a-health-hazard/," [Online].

[23] Energinet-Elsystemansvar and Dansk-Energi, "Tendenser og fremtidsperspektiver for elsystmet," 2019.

[24] "https://energinet.dk/Om-nyheder/Nyheder/2019/10/31/Anbefaling-for-elforsyningssikkerhed," [Online].

[25] IRENA, "RENEWABLE POWER GENERATION COSTS IN 2019," 2020.

[26] Energinet, "Hvad påvirker elpriserne i Danmark?," 2016.

[27] E. P. Office, "Early estimates of CO2 emissions from energy use," 2020.

[28] European-Commision, "2020 report on the State of the Energy Union pursuant to Regulation (EU) 2018/1999 on Governance of the Energy Union and Climate Action," European Commision, Brussels, 2020.

[29] ENTSOE, “Future system inertia,” 2013.

[30] S. Impram, S. V. Nese and B. Oral, “Challenges of renewable energy penetration on power systems flexibility: A survey,” *ELSEVIER,* vol. 31, 2020.

[31] E. &. ENTSO-E, “Deterministic frequency deviations - root causes and proposalts for potential solutions,” 2011.

[32] “https://energinet.dk/El/Systemydelser/Nyheder-om-systemydelser/Statistik-over-specialregulering-2020,” [Online].

Viegand Maagøe

Welcome

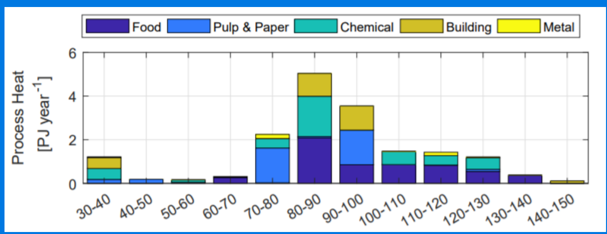
Bottlenecks for electrification

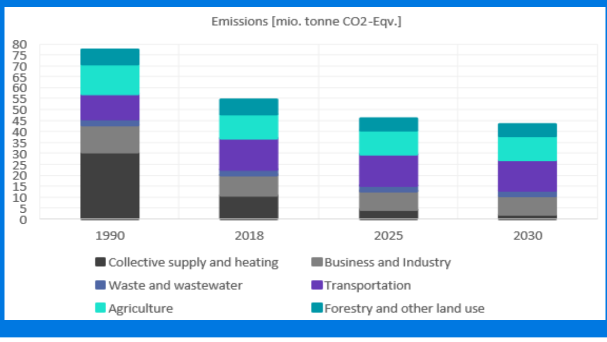
Viegand Maagøe

Background

Experience from the industry

- Many processes below 100 °C can be electrified by heat pumps
- Most thermal processes are traditionally heated by various heat transfer fluids
- CO_2 emission from the Danish industry is not expected to decrease much towards 2030
- Electrification can act as a tool to decrease emissions while securing growth and competitiveness





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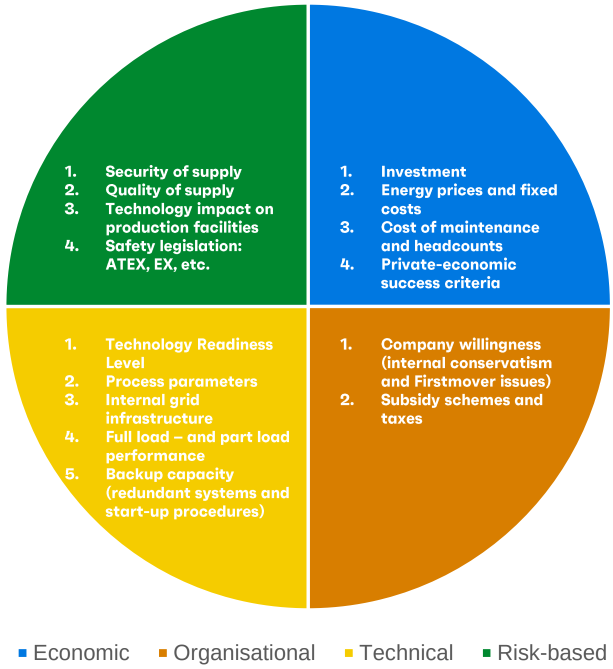
Bottlenecks for companies

Experience from the industry

- Security of supply and – quality
- Some processes are easier to electrify than others
- Energy prices and investments are problematic to successful electrification
- "Technology Readiness Level"
- Conservatism and success criteria
- Subsidy schemes, taxes, and fees



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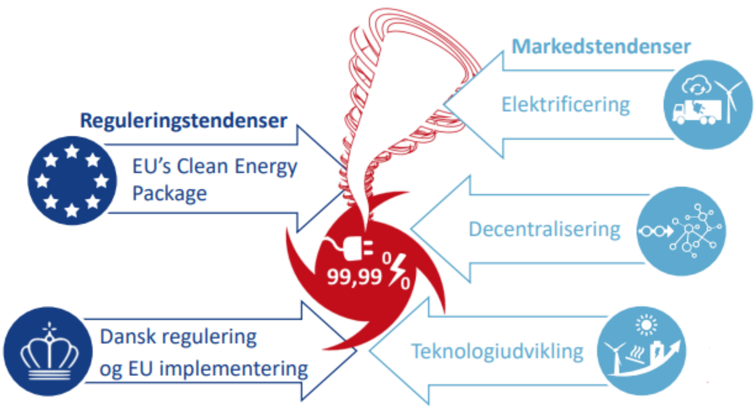
Security – and quality of supply

Experience from the industry

- Companies relying only on electricity are more dependent on security – and quality of supply
- More exposed to external breakdowns of national and/or local grid
- Increased investments in increased capacity, electric safety, and redundant systems
- Larger RES (Renewable Energy Source) penetration in the grid can cause voltage spikes and imbalances
- Construction of a secure and robust internal electricity grid is expensive



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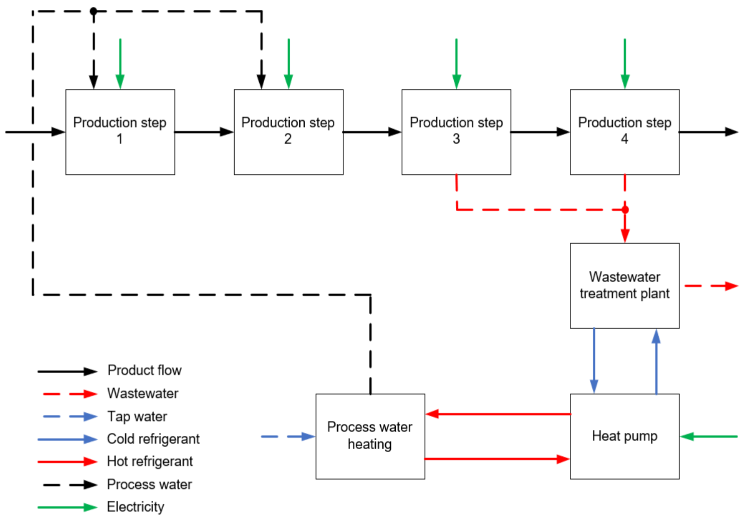
Processes and integration

Experience from the industry

- Many companies already have a system for waste heat recovery
- Electrified processes often have low - or no amounts of waste heat
- Electrification might imply restructuring of processes, which increases CAPEX
- Companies might be forced to reorganize production calendars and procedures
- Start-up procedures and utilization of waste heat within the factory



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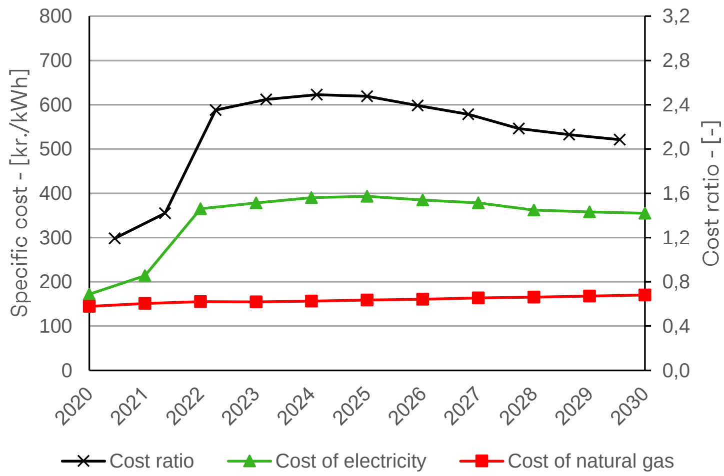
Energy prices

Experience from the industry

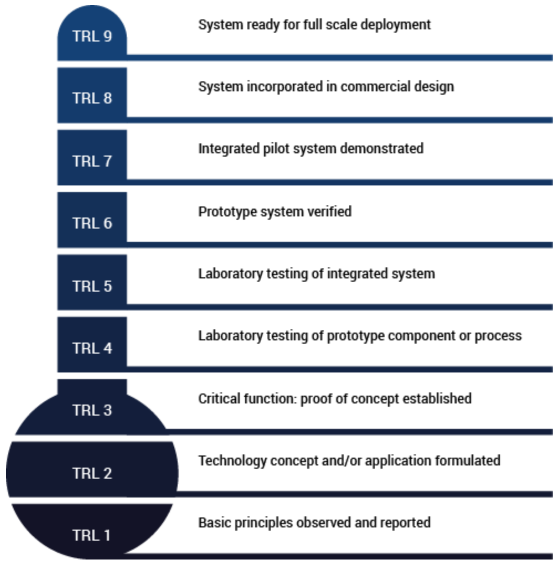
- Overriding barrier is the economy
- Spot prices from “Basisfremskrivningen”
- Including taxes, fees etc. the price ratio only decreases by approx. 5 % - (average Danish manufacturing company)
- For companies in EU ETS, cost of natural gas only increase by approx. 9 %
- In 2030, an electrified technology should have a COP of 2,1 to obtain ”brakeeven”
- Future taxes could change the picture



"Technology Readiness Level" - TRL

Experience from the industry

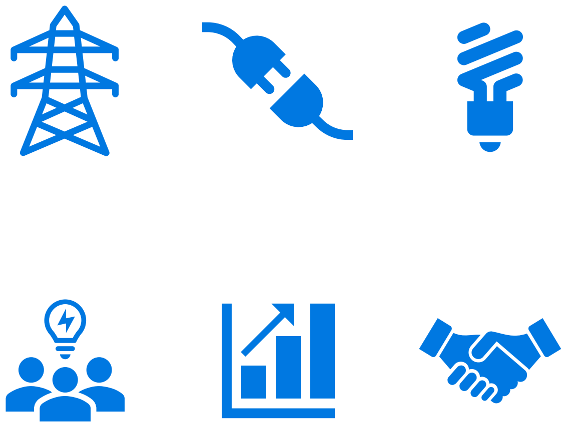
- Several processes have "plug-and-play" electrified solutions, i.e., evaporation, baking, drying etc.
- A large part of thermal processes are heated by central utility systems which can be electrified
- Electric boilers can be integrated as central utility systems → Not a feasible solution
- Technologies to compete with the price ratio have lower TRL → HTHP
- Investing in technologies under development → uncertainty



Conservatism and success criteria

Experience from the industry

- Electrification starts with the willingness to invest, to reorganize, and a complete understanding of processes
- Companies often want a broad foundation of references before investing
- Not all electric technologies have such foundation, and companies invest in development.
- Sharing of knowledge between companies to reach common targets for decarbonisation
- Internal success criteria should be re-assessed
- Marginal cost of CO_2 emission reduction?
- NPV and IRR – ignore simple payback time?



Subsidy schemes, taxes, and fees

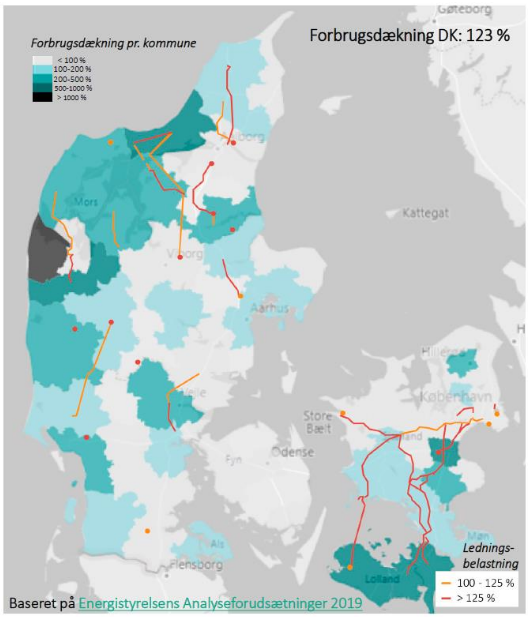
Experience from the industry

- Taxation system changes rapidly → uncertainty for companies
- Uncertainty about future trends for price ratio between electricity and fossil fuels
- Danish subsidy schemes do not embrace all energy efficiency projects → PBT limitations
- Some electrification projects do not reduce OPEX, but reduce energy consumption and emissions
- Such projects are not supported economically
- Uncertainty about future CO_2 taxation might postpone investments

RES characteristics and security of supply

Experience from the industry

- Electrification only ”really” has an impact, if electricity is generated by RES
- In DK: 98 % consumption coverage in 2021, 123 % in 2025!
- RES based electricity from can vary fast
- Higher electricity consumption leads to more RES
- Reinforcement of power grid → Challenges for the national transmission grid and increased investments
- RES contractors are to invest in reinforcement



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Danmark risikerer at bruge flere hundrede millioner eller milliarder på udbygninger, der måske alligevel ikke bliver brug for.

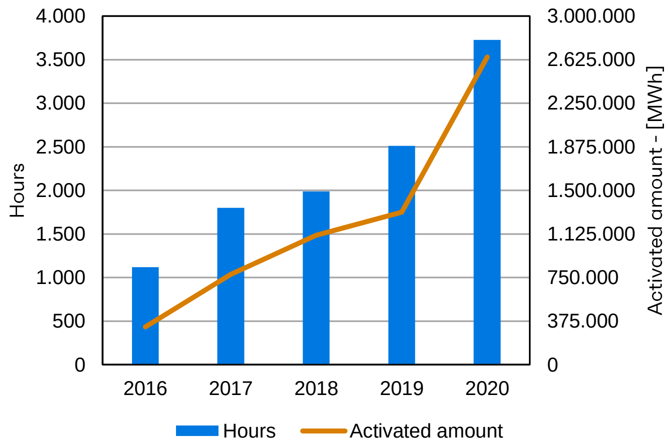
Thomas Egebo

Viegand Maagøe

Import/Export of electricity

Experience from the industry

- Import/export of electricity affects the prices
- Link to areas of higher marginal electricity prices increase the spot price
- Poor national grid infrastructure in Germany affects the DK RES potential
- DK reduces the wind turbine power generation when Northern Germany is saturated
- 2,6 TWh in 2020 → 48 % wind turbine disconnection
- Well functioning cross border connections can be key solution for ”green” electrification



Viegand Maagøe

Thanks

Juniorprojektleder

Morten Sandstrøm Petersen
Civilingeniør

+45 60 29 78 03

msp@viegandmaagoe.dk

Viegand Maagøe

Nørre Farimagsgade 37

1364 København K.

Tel. +45 33 34 90 00

B Status and technology for high temperature heat pumps

Availability of high-temperature heat pumps

Electrification of the Danish Industry

Authors

Frederik Dupond Holdt, Danish Technological Institute – Energy and Climate, fdh@teknologisk.dk

Benjamin Zühlsdorf, Danish Technological Institute – Energy and Climate, bez@teknologisk.dk

Brian Elmegaard, Technical University of Denmark – Department of Mechanical Engineering, be@mek.dtu.dk

Summary

The electrification of the Danish industry implies considerable potentials for reductions in greenhouse gas emissions, while process heating is playing an important role. An efficient electrification has the potential to increase the overall efficiency while reducing, and potentially eliminating, associated CO_2 emissions from process heat supply.

Industrial heat pumps are considered as key technology for electrifying process heat demands, as they are providing heat at highest efficiencies. The technology is a proven technology and demonstrated in several applications for heat supply in industry and district heating at supply temperatures below 100 °C. For the industrial heat supply, it may however be noted, that a large share of the process heat is required at temperatures higher than 100 °C, for which only a limited number of commercially available technologies are available.

Therefore, this project aims at giving an overview of technologies that can provide heat at high temperatures and are available commercially. Furthermore, this report gives an overview of high-temperature heat pump technologies, which are under development and expected to be available by around 2025.

It may be concluded that a set of technologies and suppliers are available, for providing heat pumps with supply temperatures above 100 °C. It may, however, also be noted that these technologies are mainly tailormade equipment, covering a limited number of applications and thus, requiring a certain effort for integrating them in industrial applications. To fully exploit a potential, further R&D focusing on technology development and process integration is inevitable.

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Contents

1. Introduction and background

Denmark has set ambitious targets with respect to reducing its climate impact. In this context, there lies a strong focus on decarbonizing industrial process heating, as it was found to be a major contributor with a considerable potential. Among the alternatives, electrification of process heating is a promising option with a variety of advantages, such as increased system efficiency, promising business cases and the reduction, and potentially a complete elimination, of CO_2 emissions.

For the majority of heating applications, industrial heat pumps are the most promising heat supply technology. For applications with supply temperatures of up to around 100 °C, there are different technologies commercially available. For higher supply temperatures, the availability of market ready solutions is rather limited.

The limited availability for applications is in contrast to the application potential, where it may be noted that the majority of applications require supply temperatures between 100 °C and 200 °C. It is furthermore expected that this temperature band will require a wide-scale adoption of so-called high-temperature heat pumps (HTHP). Considering the current application level and the ambitions for 2030, a considerable market may be expected, to satisfy the demand of technologies for this rapid transition towards 2030.

In this context, this report aims to give an overview of technologies, which are currently available for supply of process heat at temperatures above 100 °C and to provide an overview of the ongoing developments of promising technologies with an expected market entry before 2025.

This report is structured in three sections. The first chapter gives a brief introduction of the basic principles of industrial heat pump technologies and elaborates on the challenges for the development of high-temperature heat pumps. The second chapter gives an overview of currently available technologies, with a focus on natural working fluids and HFOs. Lastly, a brief overview of relevant R&D projects is given.

2. Introduction to heat pump technology

This chapter gives a brief introduction to the principles of industrial heat pumps and outlines the challenges for the development of technologies capable of supplying temperatures higher than 100 °C.

2.1. Principles of industrial heat pumps

Electrically driven industrial heat pumps are based on the same principles as industrial refrigeration systems, while the basic principles can be found in domestic heat pumps or refrigerators as well.

A typical heat pump cycle as shown in Figure 1 consists of minimum four units through which a working fluid is circulated, while it changes its state conditions, such as pressure and temperature. Typically, the working fluid is being evaporated at a low temperature, where it receives heat from a heat source, such as the ambient, solar or an excess heat stream from industrial processes or another cooling system. After the evaporation, the working fluid is being compressed to a higher temperature and pressure before it condenses while transferring heat to a heat sink. The heat sink can be a process which requires heat or a district heating network. After the condensation, the working fluid is being expanded to lower temperature and pressure before being evaporated again.

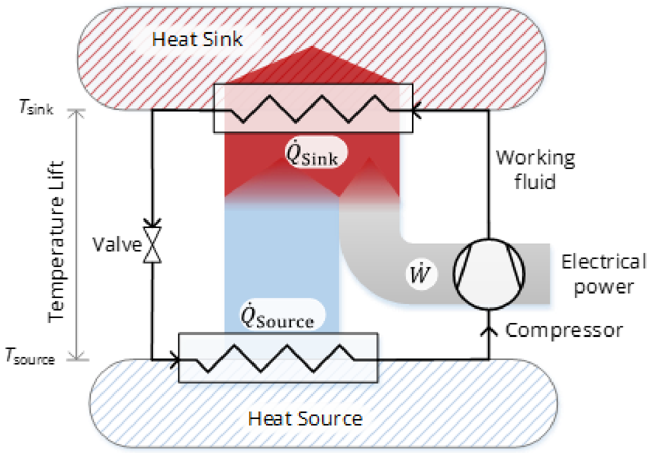

Figure 1: Diagram of a simple vapor compression heat pump cycle [1]

The amount of heat that can be supplied to a process is the sum of the heat recovered from the heat source and the electrical power which is required to compress the fluid. The amount of power, which is required to upgrade the heat from a lower to a higher temperature, is strongly dependent on the temperature lift. Larger temperature lifts require more electricity, while smaller lifts may be covered by smaller shares of electricity. The ratio of the supplied heat to the consumed electricity is called Coefficient of Performance (COP) and typically used for characterizing the performance of heat pump units.

In order to enable optimal system efficiencies, it is important to properly integrate the heat pump to ensure that the temperature lift is as small as possible. In this context, it becomes apparent that the heat should always be recovered at highest possible temperatures, while it should be supplied with lowest possible forward temperatures. The discipline of integrating processes with each other under consideration of direct heat exchange and heat pumps is referred to as *process integration*. This aspect is comprehensively addressed in remaining materials of the ELIDI project.

In addition to the boundary conditions, there is a range of design parameters, which are crucial for the design of heat pump systems as a basis for reaching optimal performances. As for all refrigeration and heat pump technologies, the selection of the working fluid is a decision, which requires to be considered in accordance with the component and system parameters. Each working fluid is showing optimal performances in a certain temperature range and therefore must be selected according to the application. In accordance with the working fluid and the operating conditions, the components must be selected and optimized. With respect to extending the operating range of heat pumps to higher temperatures, there is a special focus on the compressor.

In the following, an overview of the refrigerant selection and system design is given before a brief explanation of the compressors and the main challenges are given.

2.2. Refrigerant selection and system design

Refrigerants play a significant role in the HTHP industry, as the design parameters are based on the choice of refrigerant. All refrigerants have different properties resulting in different advantages and challenges. Each refrigerant has a certain operating range, for which promising performances may be obtained presuming sufficiently designed systems. Accordingly, there are various technologies being used and developed, to reach optimal performances [2].

The Danish industry for industrial heat pumps is dominated by manufacturers with a background in refrigeration technologies. The solutions being offered are mainly based on natural refrigerants, driven by legislative restrictions for synthetic refrigerants with a certain Global Warming Potential (GWP) and Ozone Depletion Potential (ODP).

Most of the installed large-scale heat pumps in Denmark are supplying district heating, while the majority of plants is using Ammonia (R717) as working fluid [3]. Ammonia has a working domain for which promising performances are obtained for supply temperatures of up to 90 °C but becomes challenging for higher temperatures. Therefore, ammonia receives limited attention for high-temperature applications, while there is a variety of other promising working fluids as seen in Table 1.

Table 1: Overview of working fluids for HTHP applications including associated challenges and possible improvements. Table adopted without modifications from: [4].

Working fluid	Challenges for HTHP	Existing solutions	Possible improvement
Ammonia	Material compatibility	Steel and aluminium	Enhanced material properties
	High discharge temp.	Multi-stage, intercooler integration	Cascade system with other fluids
	High discharge press.	60 bar discharge press.	-
	High toxicity	Machine room safety, glycol cycle	-
	Compressor cooling	Heat sink integrated as coolant	High temperature lubricant research
	High refrigerant inventory	Plate heat exchangers, machine room, charge mass optimization.	-
	Low performance	Flooded type evaporator, multistaging	-
CO_2	Low critical temp.	-	Combined cycle with other fluid
	High gas cooler exit temp.	Temp. glide matching, HX optimization	Integration with secondary heat sink
	High disch. press.	150 bar comp	Material, comp. tech. improvement
	Expansion device losses	Vapour recomp., expander, ejector	Further research in ejectors
	Low performance	Evaporator overfeeding	-
	Low heat sink outlet temp.	Vertical tanks for stratification	-
Water	Sub atmospheric suction press.	Heat source at or above 100 °C	Cascade in HTC with other fluid
	High disch. temperature	Intercooling between stages	Process integration with intercooler
	Low temperature lift	Multistaging	-
	High volume flow rate	Turbo comp., parallel compression	-
Hydrocarbons	Flammability	Leak detection, ventilation	-
	High discharge press.	-	Comp. technology research
	High discharge temp.	-	Lubricant, cooling system research, mixture properties
HACHP systems (Hybrid absorption-compression heat pump)	Charge mass reduction	Multiple units	-
	Sub atmospheric suction pressure	-	Mixture properties
	Large heat exchangers	-	Further research in heat transfer
	High discharge temperature	Multi-stage, intercooler integration	-
	Low performance	Internal heat exchangers	Wet compression

The group of hydrocarbons has a suitable candidate for almost all temperature ranges. While propane is most suitable for low temperatures, it is butane and pentane, which are promising for high-temperature applications. Butane is expected to show promising performances for supply temperatures up to 120 °C [5], while pentane may reach even higher.

Water (R718) has many advantages and is commonly used as heat transfer fluid in industrial process sites. Using water as working fluid has typically been challenging, due to large volume flow rates at low temperatures. However, for high-temperature applications with heat source temperatures around 100 °C, water becomes a suitable working fluid with promising performances and competitive investment cost.

CO_2 (R744) is currently available for supply temperatures of up to 110 °C to 120 °C for medium scale capacities and up to 150 °C for large-scale capacities, while it may be noted that the performances are most competitive in applications with large temperature glides on the sink side.

In addition to the more common vapor compression cycles, in which a pure working fluid is used which undergoes evaporation and condensation, there are some more further approaches being used.

Zeotropic working fluid mixtures show a temperature glide during evaporation and condensation, which allows for matching the temperature profiles with the heat source and the heat sink, and thereby enabling considerable performance improvements [1], [6]. The mixture of ammonia and water (R717/R718) is showing a large temperature glide, which requires some modifications of the standard cycle, as shown in Figure 2. In this, so called hybrid absorption-compression heat pump, the working fluid is being separated in fractions of different compositions at the outlet of the evaporator, while the gaseous part is being compressed and the liquid part is being pumped.

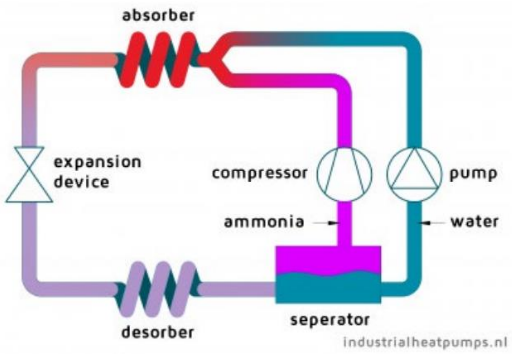

Figure 2: Example of a simple hybrid absorption-compression heat pump [7].

Further, it is possible to use working fluids which are in the gas phase throughout the cycle. Such working fluids may for example be helium (R704).

2.3. Compressors

Similarly, as all other components in the heat pump cycle, the compressor has to be designed according to the specific operating conditions and the respective component. The compressor is however working with moving parts, which creates additional challenges for the component design. Therefore, the compressor appears to be the most critical component for the development of high-temperature heat pumps.

Arpagaus et al. [8] lists various compressor types that were used in commercial installations with different refrigerants, including mono- and twin screws, piston compressors and turbo compressors. Arpagaus et al. [8] further concludes that the oil in piston and screw compressors is selected to fit the properties of the working fluid. Compatibility, viscosity and the thermal stability of the oil are all considered at high temperatures, as cooking of the oil is to be avoided. This means that POE lubricants often are used.

Some challenges regarding lubrication in HTHPs have been investigated [8] with the most significant challenges detected as:

- Loss of lubricity
- Lower oil tightness
- Chemical decomposition and coking of oil

Turbocompressors can potentially work without the need of oil in the refrigerant, which makes the indicated challenges obsolete, and are capable of high-volume flow rates. Turbocompressors are however subject to limited operating ranges and pressure ratios. Turbocompressors are well established in process industries and accordingly available for very large capacities. For smaller capacities, different technological developments are ongoing.

For R718, there have been compressors developed based on turbochargers from automobile applications, with the aim of developing highly efficient and cost-effective compression machines. These developments were documented among others by Madsbøll [9] and Zühlsdorf [10]. A figure of a prototype from the compressors is shown in Figure 3.

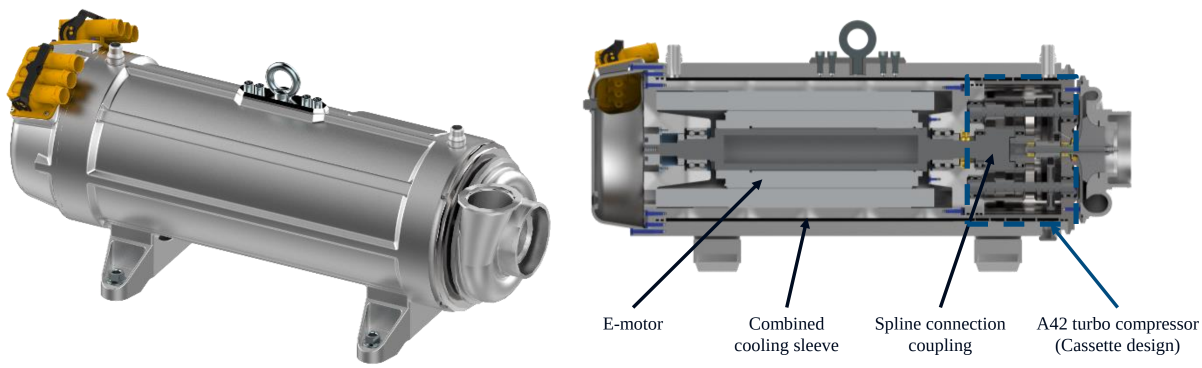

Figure 3: 3D model and sectional view of the turbocompressor based on turbochargers from automobile applications [10].

2.4. Applications of HTHPs

Industrial heat pumps are generally suitable for supply of industrial process heat, while the potential is largest for applications with a good match of heat source and sink, a high number of annual operating hours and access to electricity at low cost. Based on these criteria, certain industry branches can be identified as promising.

The Technology Data Catalogue for Industrial Process Heat [7] lists food, beverages and tobacco, commodity production, cement and non-metallic minerals, chemical industry and metals, machinery and electronics as potential sectors.

A more comprehensive estimation of the market potential for high-temperature heat pumps with supply temperatures of up to 200 °C has recently been published by Marina et al. [11]. The authors conducted a bottom-up estimation of the application potential, which has been extended to the European market, considering the pulp and paper sector, the chemical and refining sector and the food sector. The authors identified an application potential of 23.0 GW heating capacity in the named sectors in the EU 28, corresponding to an annual heat supply of 641 PJ/a. Approximately 50 % of the heating capacity is supplied by units smaller than 10 MW.

Reaching highest performances requires a sophisticated process integration. Schlosser et al. [12] analyzed a large number of recently published articles related to the HTHP industry. The article concludes that new user-friendly tools for integration and development have broken down significant barriers for the implementation of HTHPs in the process industry.

It is described how HTHPs with temperature deliveries of up to 160 °C supplying hot water, steam and hot air to supply diverse processes are market-available but due to economic framework conditions and low awareness of meaningful application among stakeholders like planners, consultants and decision-makers the market penetration is slow. The article describes how the economic profitability using HTHPs is often small, however the CO_2 savings are large which in the future may create a greater advantage in the use of HTHPs.

Finally, it is stated that most of the studies only consider the benefits of heating even though the HTHPs also have a large cooling capacity while heating. As a result, the total final energy demand and costs are related to heating which underestimates the potential of the HTHPs.

Fabian Bühler has investigated the potential for heat pumps in Denmark in his article 'The potential of heat pumps in the electrification of the Danish industry' [13]. Bühler concludes that heat pumps providing heat at up to 120 °C in the Danish industry can utilize a significant amount of excess heat to supply process heat at high COP levels. If lower COP levels are accepted, process heat supply at even higher temperatures are possible. The potential of HTHPs in the Danish industry is largely dependent on the matching between heat source and heat sink, as well as the heat sink characteristics such as temperature glide.

Bühler further concludes that the interesting HTHPs are the ones with a large excess heat source resulting in HTHPs with large capacities, but the number of excess heat sources from thermal processes above 1 MW is low (below 150), even though these few represent a large amount of the total available heat in Denmark.

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3. Market-ready HTHP technologies for applications in the Danish market

This chapter gives an overview of market-ready products. As a starting point, the literature review from Arpagaus et al. [8] is summarized before promising technologies for the Danish market are added. For the promising technologies, the current state of the development is presented and supplemented with possibilities to increase forward temperatures and an expectation of the developments during the next years.

3.1. Summary of market overview from 2018

A market overview of HTHPs has been made by Arpagaus in 2018 [8]. Arpagaus concludes that more than 20 HTHPs from 13 manufacturers have been identified in 2018 with the market steadily growing. A few of these HTHPs supply a heat sink temperature of 120 °C with the benchmark in 2018 being HeatBooster from Viking Heat Engines (not existing anymore), supplying 150 °C in heat sink temperature. In addition to this, the heating capacity of the HTHPs ranges between 20 kW and 20 MW with COP values between 2.4 and 5.8 at temperature lifts of 95 K and 40 K, respectively. The complete overview of the market as presented by Arpagaus [8] can be seen in Figure 4 including cycle layouts, compressor types, temperatures and COPs.

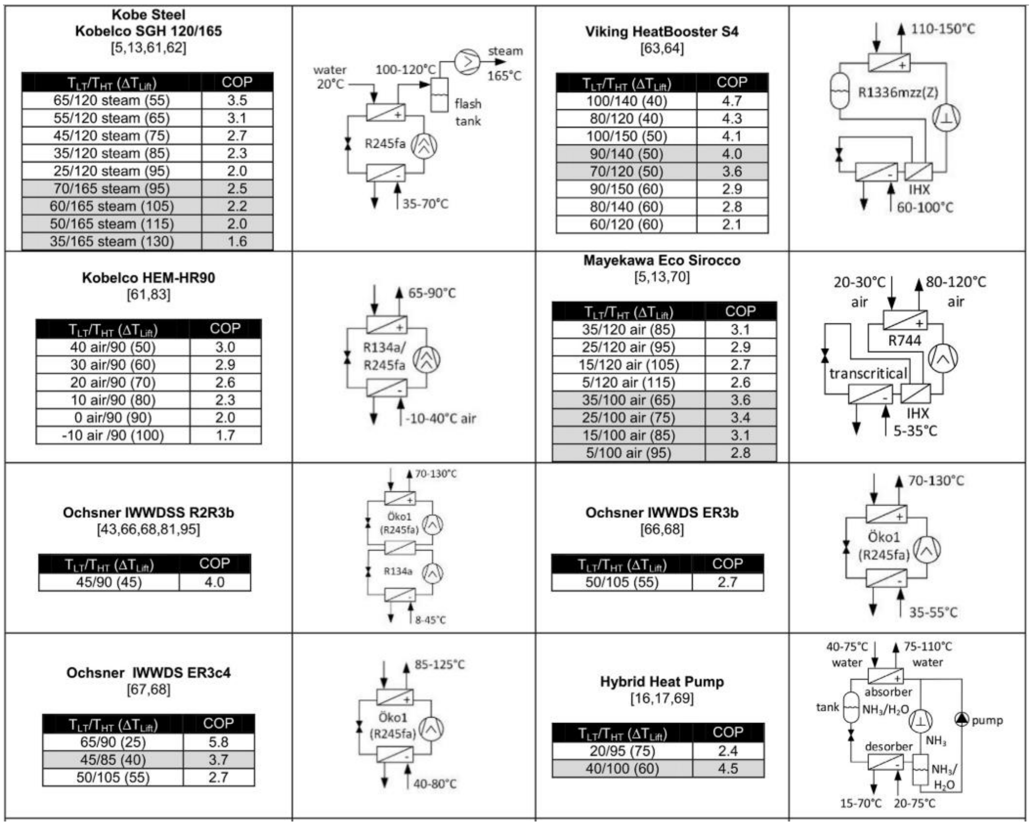

Figure 4: Market overview of HTHPs above 100 °C. Taken from: [8].

According to [8], there are numerous available refrigerants for HTHPs, all of them having different possibilities and challenges. lists several current HTHPs and their applications. Table 2, presents a list of used refrigerants for different heat sink temperatures and compressors.

Table 2: Overview of refrigerants used for HTHPs above 100 °C, Table adopted without modifications from: [8].

Manufacturer	Product	Refrigerant	Max heat sink temp.	Heating capacity	Compressor type
Kobe Steel	SGH 165 SGH 120	R134a/R245fa R245fa	165 °C 120 °C	70 kW to 660 kW 70 kW to 370 kW	Twin screw Twin screw
Viking Heat Engines	HeatBooster S4	R1336mzz(Z)/R245fa	150 °C	28 kW to 188 kW	Piston
Ochsner	IWWDS R2R3b IWWDS ER3b	R134a/ÖKO1 ÖKO (R245fa)	130 °C 130 °C	170 kW to 750 kW 170 kW to 750 kW	Screw Screw
Hybrid Energy	Hybrid Heat Pump	R717/R718	120 °C	0.25 MW to 2.5 MW	Piston
Mayekawa	Eco Sirocco	R744	120 °C	65 kW to 90 kW	Screw
Combitherm	HWWW 245fa	R245	120 °C	62 kW to 252 kW	Piston
Dürr thermea	R744	R744	110 °C	51 kW to 2,200 KW	Piston

3.2. HTHP technologies for applications in the Danish market

This chapter summarizes the technologies that could potentially be used in the Danish market and gives an overview of potential system and component manufacturers. The chapter is structured according to the refrigerants.

3.2.1. R718 – Water

Water, R718, is especially interesting as a working fluid due to the environmental advantages of using water instead of a chemical refrigerant. Water has been investigated as a refrigerant for HTHPs numerous times.

Bamigbetan et al. [4] adds that water is the safest known working fluid in the heat pump industry, almost completely free and stable with most heat pump materials. In addition to this, water has a high critical temperature making it suitable for HTHP applications.

Water has a boiling temperature of 100 °C at atmospheric pressure resulting in a typical sub-atmospheric pressure working range. This again results in a higher volume flow at the same mass flow compared to other refrigerants. Bamigbetan et al. [4] also mention that investigations have proven that water becomes more efficient as a working fluid when temperatures reach 200 °C, even with temperature lifts of around 70 K meaning that water seems to be a very effective refrigerant for HTHPs.

Zühlsdorf et al. [10] developed design recommendations for steam compression systems and argued that water as a refrigerant shows good thermodynamic and environmental performance at high temperatures, but it does require greater investment due to large volume flows compared to other refrigerants.

In Zühlsdorf et al. [14], multi-stage steam compression systems were analyzed with respect to their thermodynamic and economic performance and were found to be a promising solution, which can provide the lowest levelized cost of heat when sufficiently integrated with the processes.

Steam compression systems are commonly applied in mechanical vapor recompression systems. However, these applications do typically use roots blowers, which are relatively cost intensive with respect to maintenance. Therefore, different suppliers have focused on the development of cost-efficient solutions for heat pump applications.

In addition to the manufacturers below, Kobe Steel developed a high-temperature heat pump system that can provide supply temperatures of up to 165°C using a combination of a bottom cycle and a steam compression system. However, these systems are not available for the Danish market.

Weel & Sandvig

Weel & Sandvig is a Danish company founded by Jan Sandvig and Mogens Weel. Weel & Sandvig is a leading innovator in model-based software and industrial energy efficient solutions that deliver productivity, reliability and accuracy to their customers from a wide of industries.

Weel & Sandvig is developing and testing new high speed HTHPs using water as refrigerant. Using a small turbo compressor, Weel & Sandvig can create a temperature lift of 40 K and a compression from 1 bar to 4 bar [15].

- The HTHPs from Weel & Sandvig are most suitable for drying plants and as MVR (Manual Vapor Recompression) in evaporation plants, which is further described in the end of this section. The HTHPs are compact due to the high-speed motor integration. Initial testing of the HTHPs shows a capacity of 700 kg/h with a suction pressure of 1 bar and a COP value of 5 to 7.

Spilling

Spilling was originally founded in 1890 as a marine engineering company. The focus has shifted towards flexible and efficient decentral energy generation. The Spilling steam compressors are used when steam with a high pressure is to be generated from existing steam using low pressure steam [16].

This is used when excess low-pressure steam is recovered and is to be converted into steam with a higher pressure and temperature or when high pressure steam is to be compressed to a higher-pressure level without installing an additional boiler unit.

The adaptability of the Spilling steam compressor to the most varied steam specifications and its good controllability makes it an interesting alternative for many industrial processes. The Spilling steam compressors require inlet pressures of at least 1 bar and can compress up to a final pressure of 60 bar with a capacity of 1 to 20 t/hour. The Spilling compressors are tailormade compressors and accordingly cost intensive compared to the turbocompressors based on turbochargers from automobile industries.

ToCircle

ToCircle is a Norwegian company founded in 2003 making a new kind of rotary vane machine based on the ideas by Norwegian inventor Kjell Vading. After several years of testing at universities and Norwegian energy company Equinor (formerly Statoil), the products from ToCircle are now available on the market [17].

ToCircle is involved in the research project 'Free2Heat' which is a project developing a validated concept for high-temperature heat pumps with the main objective of developing a robust and sustainable two-phase heat pump which can be implemented in an open heat pump cycle. The heat pump cycle does not need lubrication oils, as they are using the refrigerant, water (R718) as lubrication.

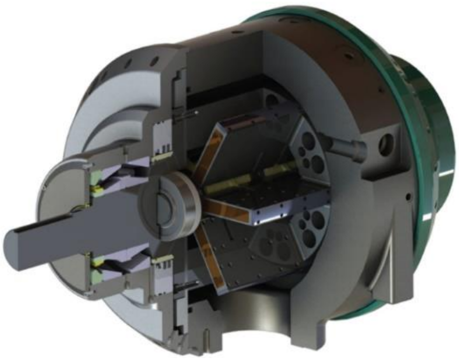

Figure 5: Principle sketch for a vane compressor from ToCircle [18].

ToCircle performed a scaled-down pilot project at its test center in Glomfjord in May 2018 that was supposed to test the compressors in high-temperature heat pumps at two-stage compression. The pilot installation is expected to build a high-temperature heat pump supplying heat to a temperature of up to 180 °C. Later, a full-sized heat pump is expected to be built in order to demonstrate both temperature lifting capacity and volume capacity for a full-size frying line [19].

Figure 6: Testing at ToCircle test facility. Source: [19].

MAN Energy Solutions

MAN Energy Solutions is a part of MAN that was formed in 2010 focusing on the energy sector. Some of MAN-ES' products are the integrally geared compressors, which are used in industrial gases, oil and gas, CO_2, urea or acid processes and can be used as fuel gas boosters for large-scale gas turbines.

The compressors do, however, have the potential to be suitable for water compression and thereby be used in R718 HTHPs. The integrally geared compressors have a maximum capacity of 60 MW and a maximum flow rate of 550,000 m^3/h [20].

Manufacturers of MVR compressors

MVR (Manual Vapour Recompression) is a technology that is used for small pressure increases obtained by compressors primarily in water system cycles. The MVR market has been researched through the PowerUp project supported by EUDP and coordinated by Weel & Sandvig. The MVR uses the process gas directly as working medium resulting in an open system cycle which means that the energy source should be a high-temperature process heat output. By using this method, energy losses in the evaporator through pressure losses and pinch temperatures can be avoided. The compressors in these applications are often turbo compressors when the suction pressure is below absolute pressures of 1 bar whereas piston and screw compressors are used when the suction pressure is above 1 bar.

Module-based systems are currently entering the market, resulting in more development and greater possibilities for market penetration for the technology. The development of micro gas-turbine systems has been made before, as companies such as Capstone, Calnetix, Turbec and Bowman Power have made these solutions for turbines meaning that high-speed turbo compression in module-based systems is possible [21]. Additional information about the MVR technology is described by GEA [22].

Selected companies supplying MVR compressors can be seen in the following:

- PILLER. The German company PILLER manufactures customized blowers and processors for the process industry and is one of the technology leaders. PILLER has a large interest in R&D and has delivered to almost all countries in the world through its over 100 years history. PILLER uses water as working medium and the main component is a PILLER MVR blower which is a high-performance system that concentrates the steam to the required pressure level in a multi-stage process. Most systems in Piller applications are operating with water, which has a high evaporation enthalpy [17].
- Howden. Howden was founded in 1854 as a marine engineering firm in Scotland. Since then, Howden has grown and evolved into a global leader in manufacturing air and gas handling solutions. Howden has been involved in the MVR industry for several decades through researching, designing, building, installation and supporting all types of rotating equipment for MVR applications. To date, Howden has installed over 2,500 installations with a range of 5 kW to 6,600 kW per compressor resulting in 1.3 million kW installed capacity in over 70 countries [23].
- Atlas Copco. Atlas Copco is a Swedish multinational industrial company that was founded in 1873 manufacturing industrial tools and equipment. Atlas Copco's Compressor Technique area creates products such as industrial compressors and vacuum solutions by using turbo

compressors suitable for the MVR technology delivering pressures of up to 205 bar and volume flows up to 560,000 m^3/h [24].

- KAESER. KAESER was founded in 1919 as a machine workshop and has grown to become one of the world's leading manufacturers and providers of compressed air products and services. The company employs approximately 7,000 people worldwide and offers products such as rotary screw compressors, blowers and dryers. The turbo blowers from KAESER can perform from 150 kW to 300 kW with flow rates up to 16,000 m^3/h and pressure differentials from 0.3 bar to 1.3 bar. The motors of the turbo blowers are oil-free, wear-free and maintenance-free [25].
- TLT-Turbo. TLT-Turbo has more than 145 years of experience and is striving to become a global supplier of industrial and power ventilation. TLT-Turbo has patented high efficiency designs that allow its products to deliver superior performance. TLT-Turbo uses hybrid bearings with steel rings combined with ceramic rollers that mean significantly lower maintenance requirements and better operational performance. The TLT-Turbo MVR fans can be operated for up to 10 years without requiring maintenance [26].
- Other companies that can be mentioned are HSD Separation (China), Kaishan (China), Kawasaki (Japan), LeHeng (China) and MECO (USA) as presented in PowerUp [21].

3.2.2. Hydrocarbons

Hydrocarbons, R290 and R600 [2], are experiencing an increased interest due to environmental friendliness (Zero ODP, negligible GWP) and good thermodynamic properties. The focus lies at R290, propane, R600, butane and R600a, iso-butane, as they are showing equal or better performance compared to synthetic refrigerants. For supply temperatures above 120 °C also pentane and iso-pentane are promising alternatives. The main challenge is, however, the flammability of the hydrocarbons, which is increased as the temperatures in the HTHPs increase. The hydrocarbons are often seen in cascade systems.

For hydrocarbons, there are different manufacturers that can provide a compressor, which is technically capable of supply temperatures beyond 100 °C. It may however be noted that these operating regimes are novel for the compressor manufacturers, which often results in a tailormade modifications, a more conservative design, shorter service internals and/or compromises in guarantee. Furthermore, there are various developments focusing on the development and demonstration of suitable oils for lubrication purposes.

A specific example of hydrocarbons in HTHPs can be found in Section 4.3 concerning a project called 'HeatUp', in which prototypes supplying heat sink temperatures of 115 °C has been constructed and demonstrated.

3.2.3. R744 – CO_2

Carbon dioxide, R744, requires transcritical operation and thereby high pressures during heat rejection in applications with high supply temperatures. The working fluid experiences a large temperature glide during heat rejection and is therefore most optimal in applications with large temperature glides. To minimize the losses during the expansion from the high pressures, different devices may be employed, including ejectors or turbines. CO_2 has become the state-of-the-art technology for supermarket refrigeration systems and is currently emerging for heat pump applications as well.

MAN Energy Solutions

MAN Energy Solutions started its production of compressors using R744 in 1990 and has installed 117 compressors up until this date. The compressor system is called HOFIM, High-Speed Oil-Free Integrated Motor compressor, which is used in pipelines, gas storage, gas export and in subsea applications [27].

The HOFIM compressor system is used in MAN-ES' ETES system, Electro-Thermal Energy Storage, which is a system that can distribute heat, cold and electricity from a central area. The working principle of the ETES charging cycle is seen in Figure 7. MAN-ES aims for capacities of several megawatts.

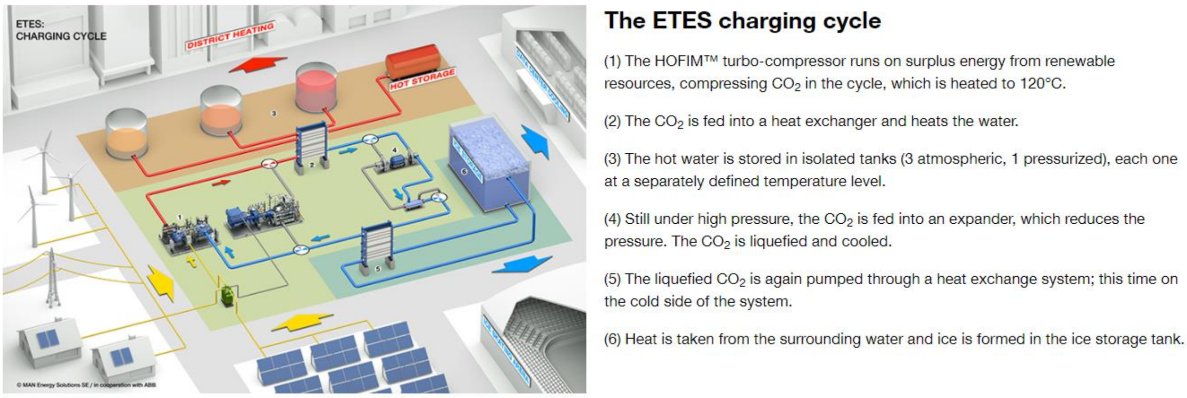

Figure 7: ETES Charging cycle from MAN-ES [27].

MAN-ES has been awarded the contract for the largest seawater heat pump in the world in Esbjerg, Denmark with a capacity of 50 MW which can supply 25.000 customers with heat. The heat pump will be based on the ETES system using R744 as refrigerant generating heat at up to 150 °C [28].

FENAGY

The Danish company FENAGY was formed in 2020 focusing on production of effective and environmental-friendly HTHPs using R744 as refrigerant. FENAGY produces HTHPs in the capacity range of 200 kW to 1800 kW and states that its HTHPs are the most effective and stable on the market.

The HTHPs by FENAGY are able to deliver heat at up to 80 °C using a single-stage system and are heating the heat sink directly using a heat source between -20 °C and 20 °C. CO2 HTHPs demand a high design pressure, as FENAGY states that the low pressure side in its system cycles is approximately 80 bar and its high pressure side is approximately 130 bar depending on design temperature. Generally, FENAGY suggests that CO_2 HTHPs have the best performance compared to other HTHPs when the temperature difference between heat source and heat sink is above 30 K [29]. FENAGY is currently evaluating possibilities to increase possible supply temperatures and is testing temperature deliveries above 100 °C.

Engie

Engie is a French multinational electric utility company which operates in the fields of energy transition, electricity generation and distribution, natural gas, nuclear, renewable energy and petroleum. Engie has 160,000 employees.

Engie is building CO_2 chillers and CO_2 high-temperature heat pumps enabling water delivery at up to 120 °C with a capacity of 1460 kW using its tried and tested technology of semi-hermetic reciprocating compressors and heat exchangers with oil separators and oil collectors specifically developed for CO_2 applications [30].

GEA Process Engineering

GEA Process Engineering is a part of the GEA group. GEA was founded in 1881 and employs 18,642 across its focus areas. GEA is looking at integrating CO_2 heat pumps into the spray drying process by using the large temperature glide of CO_2 to generate a high temperature rise of the heat sink [13].

The process is made possible using Bock compressors that enable discharge temperatures of 150 °C and pressures of 130 bar under continuous operation with a maximum allowable suction gas temperature of 40 °C. GEA has already built a prototype with a total heating capacity of 90 kW and heat sink temperatures of up to 135 °C.

The next for GEA is simultaneous generation of high and low temperature water for both heating and cooling demands in the industry. Furthermore, GEA is researching how to make the optimal process integration into spray drying plants to maximize plant energy savings.

GEA is also looking into improvements of the prototype in order to generate higher air temperatures through better heat transfer from the refrigerant to air. Another next step for GEA is to create an automated control system for water circuits and build industrial scale prototypes with a heating capacity above 1.5 MW.

3.2.4. Hybrid compression absorption heat pump using R717 and R718

Mixtures of ammonia and water can be used in a hybrid absorption-compression heat pump cycle, which is similar to a conventional vapor compression cycle with a pump operating in parallel to the compressor. This enables to control the temperature glide of the zeotropic working fluid mixture and thereby application specific optimization. Currently, Hybrid Energy is the most established manufacturer of these systems.

Hybrid Energy

The Norwegian company Hybrid Energy was formed in 2004 as a result of a breakthrough made by Norway's Institute for Energy Technology (IFE) [31]. The heat pump is operating at standard pressure (25 bar) using a mixture of water and ammonia to generate heat. The usual heat pumps using a design pressure of 25 bar can generate heat at up to 50 °C, but by using the mixture and their patented heat pump system, sink temperatures of up to 120 °C are possible. The mixture allows the refrigerant to have gliding temperatures in the absorber/condenser and desorber/evaporator. A visualization of the system can be seen in Figure 8.

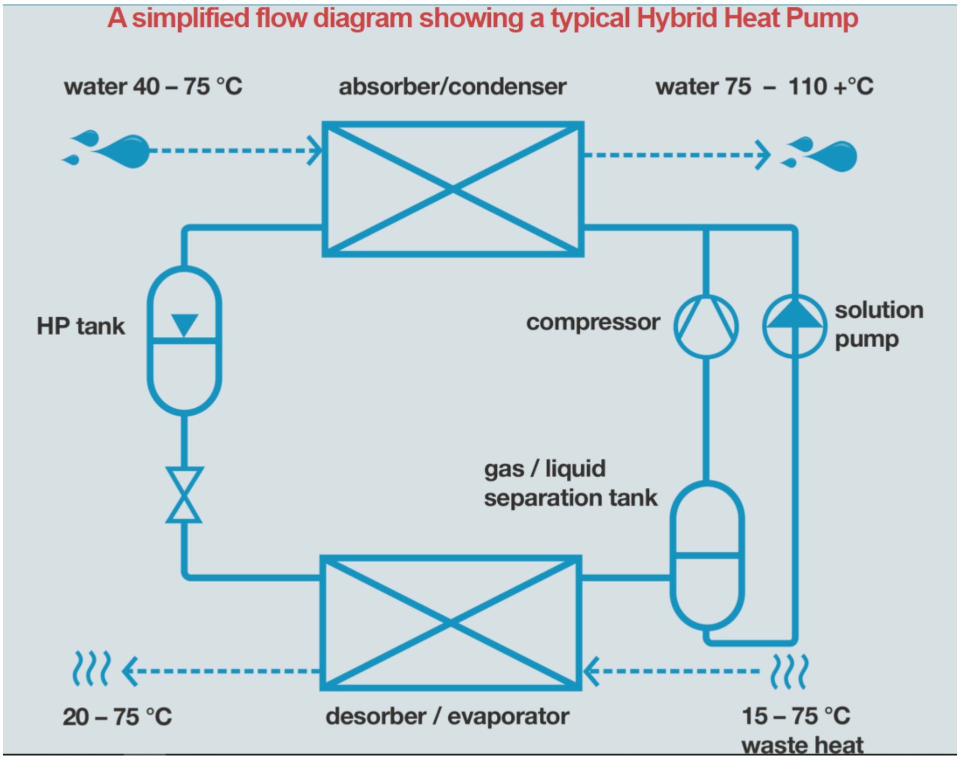

Figure 8: Flowsheet of hybrid heat pump [31].

Hybrid Energy has numerous working plants in Northern Europe at companies such as Arla meaning that there is proof of concept.

Various studies [32]–[34] have indicated that the hybrid heat pump technology is able to supply even higher temperatures with standard components when optimizing the mixing ratio and the circulation factor. Jensen 2016 [34] concluded that the technology has the potential to supply temperatures of up to 150 °C at competitive performances using available equipment.

3.2.5. R704 – Helium

R704 is not commonly used as refrigerant used in HTHPs. Olvondo Technology is, however, using it for its HTHPs in a Reverse Stirling process as seen in the section below.

Olvondo

The Norwegian company Olvondo Technology was formed in 2016 [35] and is using a technology named HighLift, enabling sink temperatures of up to 200 °C. The technology is based on the Stirling process with helium, R-704, as refrigerant and has a potential heat capacity of 700 kW. The heat pump is a four-cylinder double-acting engine with four gas circuits. The schematic overview can be seen in Figure 9.

Olvondo Technology has delivered HTHPs to several customers which combined have been active for more than 50,000 hours. Olvondo Technology is categorizing its HTHPs as the only industrial very high-temperature heat pump based on a Reverse Stirling process. The stability and effectiveness of the HTHPs has not been analyzed.

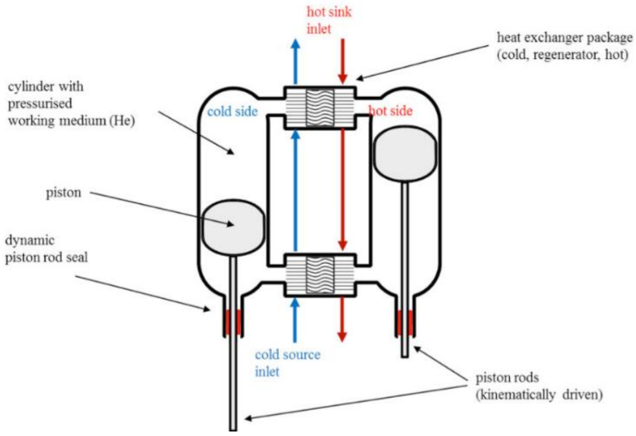

Figure 9: Diagram of Olvondo Technology working principle [35].

3.2.6. HFOs

HFOs have been investigated and described and discussed by V. Nair [36]. In the article, HFOs are primarily compared to HFCs with high GWP. HFOs are not natural and will therefore have an impact on the environment, even though it may be hard to quantify the exact impact. V. Nair [36] furthermore points on the advantages of HFOs compared to hydrocarbons due to lower flammability of HFOs.

Viking Heat Engines

Viking Heat Engines was founded in 2009 in Norway. Currently, Viking Heat Engines has locations in Norway and Germany and uses its unique piston compressor technology to build HTHPs using HFOs. Viking Heat Engines uses R1234ze, R13336mzz(E) and R13336mzz(Z) as refrigerants for its HTHPs and can deliver heat sink temperatures up to 160 °C stating that it builds the hottest closed loop heat pumps on the market. Viking Heat Engines has built HTHPs with a capacity range of 50 kW to 4,000 kW. [37]. Viking Heat Engines went bankrupt in 2020 [38].

The Viking Heat Engines technology has been acquired by the new company Heaten, which is seeking to continue the development.

OCHSNER

OCHSNER is a family business with roots going back to 1872. The heat pump area of OCHSNER, OCHSNER Wärmepumpen GmbH, was formed in 1978 and was one of the first European manufacturers to manufacture heat pumps on an industrial scale and is today one of the sector's international leaders.

OCHSNER is producing heat pumps compatible with every heat source. The heat pumps can deliver capacities of 2 kW to 2,500 kW with flow temperatures of up to 130 °C using HFC refrigerants such as R245fa. The heat pumps for high-temperature demands use scroll compressors in special high-temperature design [39].

Siemens

Siemens has analyzed the possibilities of using HFO refrigerants for high-temperature heat pumps. The studies are documented by [40], [41] and included both numerical studies and experimental laboratory tests. Two working fluids, namely MF2 and LG6, were tested and found to be promising. The experiments indicated possible supply temperatures of up to 140 °C at satisfying efficiencies.

4. Research projects and initiatives

It is expected that the transition towards electrified process heat supply will require rapid changes and the implementation of various technologies between 2025 and 2030. In this context, this chapter gives an overview of the selected R&D projects working on bringing technologies to the market by 2025.

An overview of R&D projects involving experimental setups has been presented by [8] in 2018, as shown in Figure 10. The highest heat sink temperature achieved is currently 160 °C at a heat source temperature of 110 °C using a single-stage closed-cycle layout with a piston compressor, an internal heat exchanger and R1336mxx(X) as refrigerant.

Organisation, Project partners	Cycle type	Compressor	Refrigerant	Heat source (grey) and heat sink (black) temperatures [°C] (20 40 60 80 100 120 140 160)	Heating capacity [kW]	Authors (year) [references]
Austrian Institute of Technology, Vienna, Chemours, Bitzer	Single-stage with IHX	Piston	R1336mzz(Z)		12	Helminger et al. (2016) [103]
Austrian Institute of Technology, Vienna, Chemours, Bitzer	Single-stage	Piston	R1336mzz(Z)		12	Fleckl et al. (2015) [50,104]
PACO, University Lyon, EDF Electricité de France	Flash tank	Twin screw	R718		300	Chamoun et al. (2014, 2013, 2012) [107–110]
Institute of Air Handling and Refrigeration, Dresden, Germany	Single-stage	Piston	HT 125		12	Noack (2016) [37]
Friedrich-Alexander Universität Erlangen-Nürnberg, Siemens, Germany	Single-stage with IHX	Piston	LG6		10	Reißner et al. (2015, 2013) [89,106,111]
Alter ECO, EDF Electricité de France	Single-stage with IHX and subcooler	Twin scroll	ECO3 (R245fa)		50 to 200	Bobelin et al. (2012) [7], IEA [5]
Tokyo Electric Power Company, Japan	Single-stage	Screw	R601		150 to 400	Yamazaki and Kubo [112]
Austrian Institute of Technology, Vienna, Edtmayer, Ochsner, Austria	Single-stage with economizer	Screw	ÖKO1 (R245fa)		250 to 400	Wilk et al. (2016) [105]
Tianjin University, China	Single-stage	Scroll	BY-5		16 to 19	Zhang et al. (2017) [113]
Kyushu University, Fukuoka, Japan	Single-stage	Twin rotary	R1234ze(Z)		1.8	Fukuda et al. (2014) [114]
ECN, SmurfitKappa, IBK, Bronswerk, The Netherlands	Single-stage with IHX and subcooler	Piston	R600		160	Wemmers et al. (2017) [115]
Korea Institute of Energy Research, Daejeon, Korea	Single-stage with steam generation	Piston	R245fa/R718		20 to 40	Lee et al. (2017) [116]
GREE Electric Appliances, Zhuhai, China	Single-stage	Scroll	R245fa		6 to 12	Huang et al. (2017) [117]
Norwegian University of Science and Technology, SINTEF	Two-stage cascade	Piston	R600/R290		20 to 30	Bamigbetan et al. (2017) [118,119]
TU Graz, Austria	Single-stage with IHX	Piston	R600		20 to 40	Moisi et al. (2017) [120]
Tianjin University, China	Single-stage	Double scroll	BY-4		44 to141	Yu et al. (2014) [121]
EDF Electricité de France, Johnson Controls	Single-stage with IHX and economizer	Twin screw, centrifugal turbo	R245fa		300 to500 900-1'200	Assaf et al. (2010) [122], IEA (2012, 2014) [5,87], Peureux et al. [6]

Figure 10: Overview of current research projects of HTHPs. Taken from: [8].

4.1. DryFiciency

The DryFiciency project is an international four-year innovation action funded by the Horizon 2020 program. It aims at demonstrating two technologies with a generic design and provide at certified training programme. The considered technologies were two closed-loop HFO heat pump systems and an open-loop system based on direct steam compression with turbo-compressors. The three demonstrations are drying of starch in the food industry, brick drying and wastewater purification. An overview of the project and the available publications can be found under [42].

The heat pump demonstrations have a capacity of approx. 400 kW with a heat source temperature of 70 °C and a heat sink temperature of 160 °C using water as refrigerant.

The heat pump demonstration system for the food industry is made for Agrana, a leading Austrian company adding value to agricultural commodities. For this setup, the heat pump is placed in a container outside the starch plant and the heat pump is used to assist the starch drying process.

The heat pump for the brick industry is placed at Wienerberger, the world's largest producer of bricks and number one in the clay roof tiles market in Europe. The demonstration heat pump is placed in a container and shall replace a natural gas burner and thereby lead to energy savings of up to 84% and reductions in CO_2 emissions of about 80%. The heat pump will be created as a twin-cycle configuration with two refrigerant cycles.

The heat pump demonstration system for waste management is placed at Scanship. Scanship produces advanced wastewater purification and waste management systems for the marine industry as well as land-based waste management systems. The heat pump demonstration system will be an open loop system using oil-free Rotrex turbo-compressors and aims to reduce the dryer's energy demand by up to 75%.

4.2. HeatUp

HeatUp is a Norwegian research project starting in 2015 with financial support from the Norwegian Research Council. The project started in May 2015 with a project period of 4 years with the purpose of increasing the HTHP temperature range up to 200 °C by using natural refrigerants such as butane, ammonia (R717) and water (R718).

The HeatUp project reached a major milestone in 2017 after installing a prototype using propane and butane that was able to deliver thermal energy at 110 °C to 120 °C. The installation uses a heat source temperature of 30 °C resulting in temperature lifts of up to 100 K with a capacity of up to 200 kW [43].

Figure 11: Installed prototype from HeatUp project. Source: [43]

An article was published by Bamigbetan et. al in 2019 as a part of the HeatUp project. The article, 'The development of a hydrocarbon high-temperature heat pump for waste heat recovery', covers a test of a cascade heat pump using propane in the low temperature region and butane in the high temperature region generating a temperature lift from 30 °C up to 115 °C. The prototype was tested with temperature lifts of 58 K to 72 K with an average COP of 3.1 resulting in an environmentally friendly system compares to existing solutions of a steam boiler [44].

An economic analysis has been made in the article comparing HTHPs using heat sources at 30 °C and 60 °C respectively with direct electricity and a gas boiler as heat sources in Figure 12. It is hereby seen that after 10 years, both HTHPs are cheaper than direct electricity and a gas boiler when delivering heat at 115 °C.

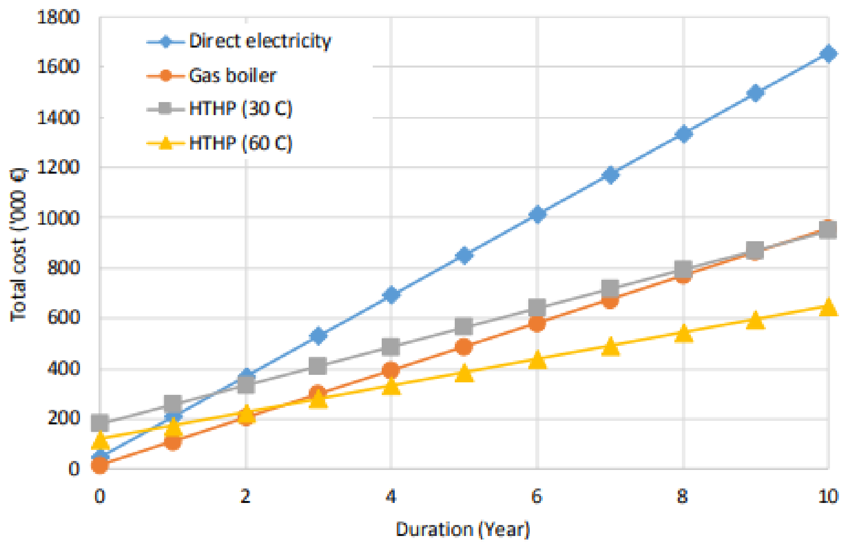

Fig. 11. Cost comparison between HTHP at 30 °C and 60 °C waste heat temperature to conventional heat systems. Heat delivery at 115 °C.

Figure 12: Comparison of economic results using different energy sources. Source: [44].

4.3. SuPrHeat

A current development project, *SuPrHeat – Sustainable process heating with high-temperature heat pumps using natural refrigerants*, was started in September 2020 with an expected end in August 2024 [45]. The project aims to develop three high-temperature heat pump systems to be used for creating process heat supply at temperatures of up to 200 °C using natural refrigerants at a thermal supply capacity of around 500 kW each.

The heat pump development comprises three main activities:

- System design and component development
- System testing at a variety of operating and potentially required modifications
- Long-term testing at end-users

These activities imply the potential to develop and test novel technologies under a variety of operating conditions, before the technologies are to be tested in an industrial context at end-users.

The project will furthermore develop methods for improved process integration considering both existing production sites and new process equipment, such as spray dryers, freeze dryers and evaporators. The primary target group of the technologies is the food and beverage sector.

A visualization of the preliminary temperature targets in the SuPrHeat project can be seen in Figure 13.

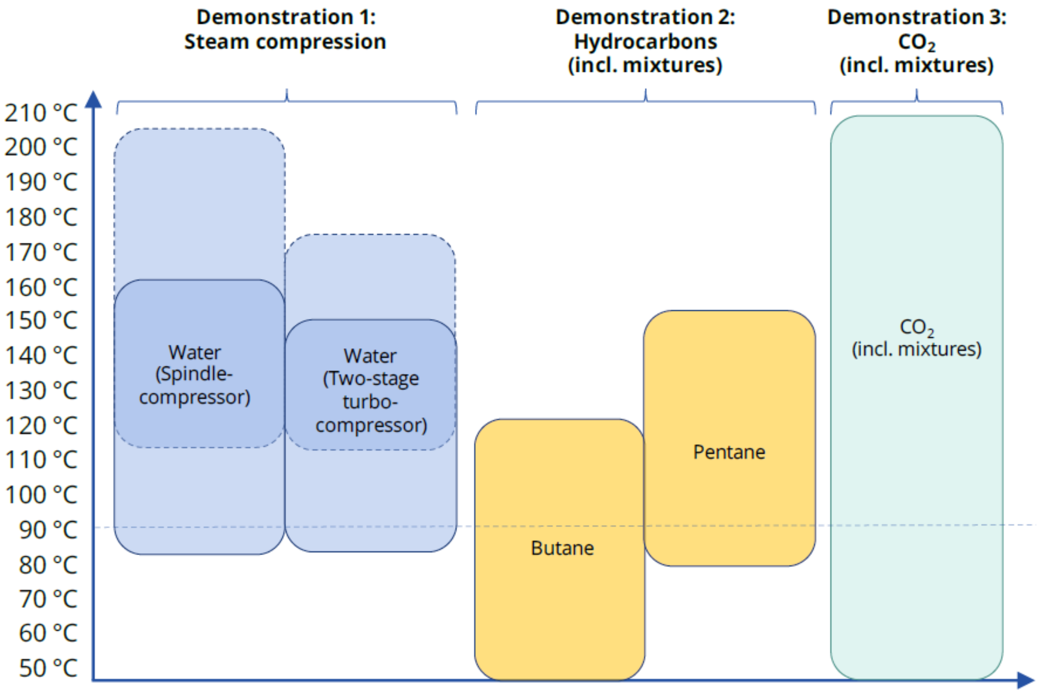

Figure 13: Target temperature ranges for natural refrigerants in SuPrHeat [45].

The three technologies were chosen to supplement each other and thereby constitute a portfolio, implying technologies that are able to reach highest thermodynamic and economic performances at a large range of applications.

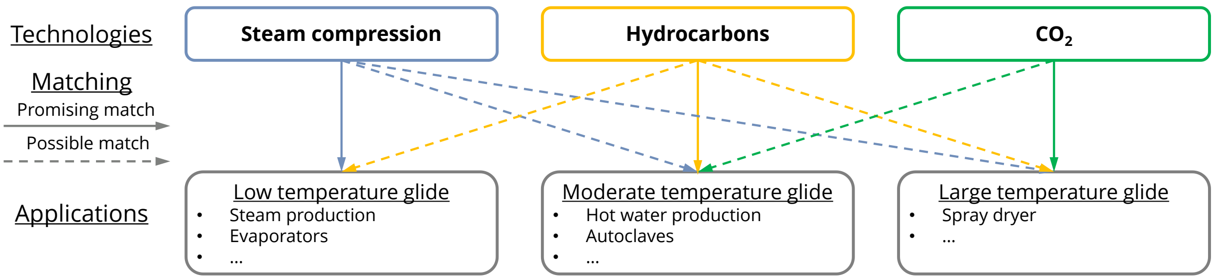

Figure 14: Technology portfolio and possible applications to be developed within the SuPrHeat project [45]

4.4. Development of steam compression systems for tunnel ovens

Tunnel ovens are the standard method for a number of baking processes for bread, biscuits, cookies, etc.. The temperature level is typically in the range of 180 °C to 250 °C. An ongoing ELFORSK project ELFORSK 352-009 (High temperature heat pump for tunnel oven) aims to develop a heat pump for these temperature levels with water vapor as refrigerant, the built-in pressure ratio corresponds to supply temperature 230 °C at 110 °C inlet conditions. Figure 15 shows the compressor to the left (Hamburg Vacuum) and the special spindle being manufactured by CSTechcom to the right.

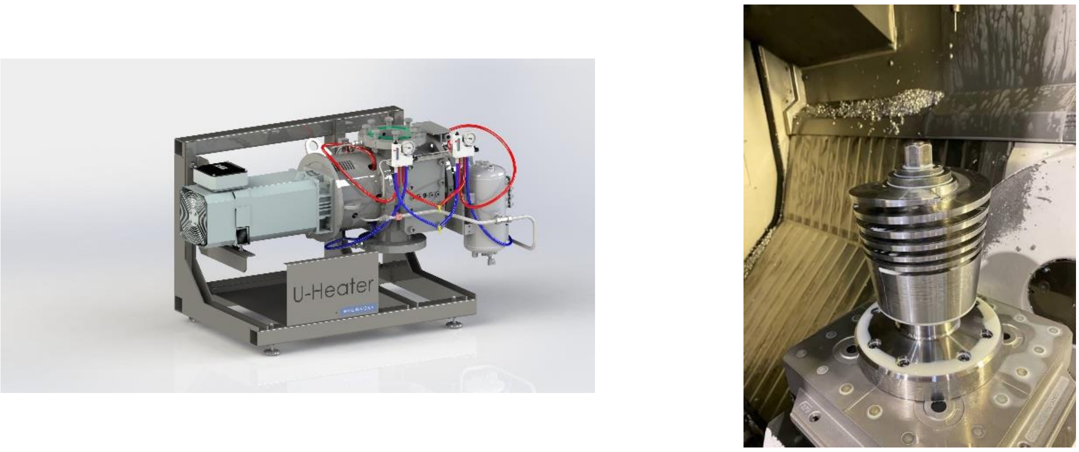

Figure 15: Spindle compressor from Hamburg Vacuum (left) with spindle during production at CSTechcom

In order to meet the inlet conditions of 110 °C the spindle compressor will be combined with a turbocompressor being developed in an ongoing Innobooster project (Innovativ høj temperaturs varmepumper) developing a direct drive high speed turbo compressor (CSTechcom) for lifting water vapor from 80 °C to 110 °C conditions. Both compressors will be tested in Mai 2021.

In the DryF project another gear driven turbo compressor is developed by Rotrex for temperature lift conditions from 100 °C to 120 °C.

Figure 16 shows the Rotrex compressor to the left and the direct drive high speed compressor to the right.

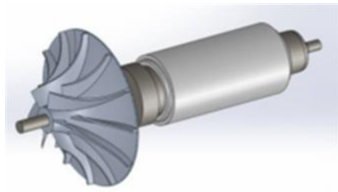

Figure 16: Rotrex turbo compressor (left) and direct driven turbo compressor (right)

4.5. White paper "Strengthening Industrial Heat Pump Innovation – Decarbonizing Industrial Heat"

The current situation of R&D on industrial heat pumps has been investigated by De Boer et al. in 2020 [46]. The whitepaper highlights a large application potential for industrial heat pumps and various applications have been outlined.

Due to the large potential and the expected technology demand for high-temperature heat pumps to facilitate the decarbonization of the industry, it is apparent that further developments are needed to develop viable and competitive solutions covering the potential between 100 °C to 200 °C in supply temperatures. Therefore, the White Paper suggests a set of coherent measures, including:

- Creating fair regulatory frameworks facilitating the acceptance of industrial heat pumps
- Setting up a European information and knowledge base for heat pump technologies and process integration
- Establishing an RD&D program supporting and strengthening growth of industrial heat pump applications

5. Conclusions

High-temperature heat pumps were found to have a considerable potential for electrifying industrial process heat demand, while increasing the overall energy efficiency. The majority of applications requires supply temperatures above 100 °C, while currently available equipment is mainly limited to temperatures below 100 °C. Technologies which can reach higher temperatures are under development and currently at lower technology readiness levels.

In order to fully exploit the potential of high-temperature heat pumps in the developments towards 2030, it is required to create a common understanding of the technology, its potentials and its perspectives at a variety of stakeholders.

This report summarizes the current state of the art of high-temperature heat pumps including technologies, which may become available for the Danish market by 2025. Thereby, the report creates a basis for energy planning and identifying further R&D needs.

The report condensed the results from previous international state of the art reviews and supplemented the findings with technologies that are relevant to the Danish market. The overview was structured according to the working fluids, namely water (R718), hydrocarbons, CO_2 (R744), HFOs, Helium (R704) as well as mixtures of water and ammonia in a hybrid system. For all working fluids, most relevant manufacturers were summarized including potential applications and perspectives for further developments.

Lastly, most relevant R&D projects were presented, which are fostering the development and demonstration of high-temperature heat pumps.

From this overview, it may be concluded that a variety of technologies may become available for the market by 2025. It becomes however apparent, that further R&D activities are needed for further advancing the technologies and bringing them closer to the market. A dedicated R&D effort has the potential to establish the Danish industry in a pivotal role for both the technology development of industrial heat pumps, as well as providing the end-users with the market advantage of having first access to these key technologies. The required activities include technological developments, but also demonstration projects and focus on process integration. In addition to the R&D developments, a broad knowledge base has to be created, targeting for various stakeholders and contributing to the creation of fair regulatory frameworks.

6. References

[1] B. Zühlsdorf, "High-performance heat pump systems - Enhancing performance and range of heat pump systems for industry and district heating," Technical University of Denmark, 2019.

[2] P. H. Jørgensen, B. Elmegaard, and B. Zühlsdorf, "Danish Report of Task 2 for Annex 48 'Industrial Heat Pumps, Second Phase' as part of the IEA HPT TCP," 2019.

[3] B. Zühlsdorf, F. Bühler, P. H. Jørgensen, and B. Elmegaard, "Danish Report of Task 1 for Annex 48 'Industrial Heat Pumps, Second Phase' as part of the IEA HPT TCP," 2019.

[4] O. Bamigbetan, T. M. Eikevik, P. Nekså, and M. Bantle, "Étude De Pompes À Chaleur À Compression De Vapeur Pour Le Chauffage Haute Température À L'Aide De Fluides Actifs Naturels," *Int. J. Refrig.*, vol. 80, pp. 197–211, 2017, doi: 10.1016/j.ijrefrig.2017.04.021.

[5] O. Bamigbetan, T. M. Eikevik, P. Nekså, M. Bantle, and C. Schlemminger, "Theoretical analysis of suitable fluids for high temperature heat pumps up to 125 °C heat delivery," *Int. J. Refrig.*, vol. 92, pp. 185–195, 2018, doi: 10.1016/j.ijrefrig.2018.05.017.

[6] B. Zühlsdorf, J. K. Jensen, and B. Elmegaard, "Heat pump working fluid selection - Economic and thermodynamic comparison of criteria and boundary conditions," *Int. J. Refrig.*, vol. 98, pp. 500–513, 2019, doi: 10.1016/j.ijrefrig.2018.11.034.

[7] Danish Energy Agency and Energinet, "Technology Data - industrial process heat," 2020.

[8] C. Arpagaus, F. Bless, M. Uhlmann, J. Schiffmann, and S. S. Bertsch, "High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials," *Energy*, vol. 152, pp. 985–1010, 2018, doi: 10.1016/j.energy.2018.03.166.

[9] H. Madsbøll, M. Weel, and A. Kolstrup, "Development of a Water Vapor

Compressor for High Temperature Heat Pump Applications," in *Proceedings of International Congress on Refrigeration*, 2015, p. Paper ID 845.

[10] B. Zühlsdorf, C. Schlemminger, M. Bantle, K. Evenmo, and B. Elmegaard, "Design recommendations for R-718 heat pumps in high temperature applications," *Refrig. Sci. Technol.*, vol. 2018-June, no. c, pp. 1101–1110, 2018, doi: 10.18462/iir.gl.2018.1367.

[11] A. Marina, S. Spoelstra, H. A. Zondag, and A. K. Wemmers, "An estimation of the European industrial heat pump market potential," *Renew. Sustain. Energy Rev.*, vol. 139, p. 110545, 2021, doi: 10.1016/j.rser.2020.110545.

[12] F. Schlosser, M. Jesper, J. Vogelsang, T. G. Walmsley, C. Arpagaus, and J. Hesselbach, "Large-scale heat pumps: Applications, performance, economic feasibility and industrial integration," *Renew. Sustain. Energy Rev.*, vol. 133, no. March, p. 110219, 2020, doi: 10.1016/j.rser.2020.110219.

[13] F. ; Bühler, B. ; M. Zühlsdorf, F. Müller Holm, and B. Elmegaard, "The potential of heat pumps in the electrification of the Danish industry," *2nd Symp. High-Temperature Heat Pumps. SINTEF*, pp. 51–67, 2019.

[14] B. Zühlsdorf, F. Bühler, M. Bantle, and B. Elmegaard, "Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C," *Energy Convers. Manag. X*, vol. 2, no. January, p. 100011, 2019, doi: 10.1016/j.ecmx.2019.100011.

[15] Weel & Sandvig, "Heat Pump Technologies – Weel & Sandvig," 2021. https://weel-sandvig.com/heat-pump-technologies/ (accessed Jan. 28, 2021).

[16] Spilling Technologies, "Steam Compressors," 2021. https://www.spilling.de/products/steam-compressors.html (accessed Jan. 28, 2021).

[17] ToCircle, "ToCircle Industries," 2021. https://tocircle.com/box/about (accessed Feb. 09, 2021).

[18] M. Bantle, "Free2Heat - SINTEF," 2019. https://www.sintef.no/en/projects/2019/free2heat/ (accessed Feb. 10, 2021).

[19] CORDIS, "Periodic Reporting for period 1 - Hot chips (Waste heat recovery for industrial heat intensive processes) | Report Summary | Hot chips | H2020 | CORDIS | European Commission," 2019. https://cordis.europa.eu/project/id/805689/reporting (accessed Feb. 09, 2021).

[20] M. E. Solutions, "Integrally geared compressors from MAN Energy Solutions," 2021. https://www.man-es.com/process-industry/products/compressors/integrally-geared-compressors (accessed Feb. 11, 2021).

[21] Weel & Sandvig, "PowerUp," no. 64018, 2020, [Online]. Available: https://weel-sandvig.com/wp-content/uploads/2020/10/ws-powerup-dansk-fllesrapport-v3.pdf.

[22] MAN Energy Solutions, "A tale of fire and ice," 2021. https://www.man-es.com/discover/a-tale-of-fire-and-ice (accessed Jan. 28, 2021).

[23] H. Bjerre-Christensen, "Esbjerg får verdens største grønne havvandsvarmepumpe fra Schweiz | jv.dk," 2021. https://jv.dk/artikel/esbjerg-får-verdens-største-grønne-havvandsvarmepumpe-fra-schweiz (accessed Jan. 28, 2021).

[24] FENAGY, "Fenagy CO2 VP og funktion og design," 2021. https://www.fenagy.dk/fenagy-co2-vp-funktion-og-design (accessed Jan. 29, 2021).

[25] Engie, "Optimal use of energies. CO 2 chillers and CO 2 high temperature heat pumps," 2021.

[26] Hybrid Energy, "Technology overview – Hybrid Energy," 2021. https://www.hybridenergy.no/tech-overview/ (accessed Jan. 25, 2021).

[27] J. K. Jensen, W. B. Markussen, L. Reinholdt, and B. Elmegaard, "On the development of high temperature ammonia-water hybrid absorption-compression heat pumps," *Int. J. Refrig.*, vol. 58, pp. 79–89, 2015, doi: 10.1016/j.ijrefrig.2015.06.006.

[28] J. K. Jensen, T. Ommen, W. B. Markussen, L. Reinholdt, and B. Elmegaard,

"Technical and economic working domains of industrial heat pumps: Part 2 - Ammonia-water hybrid absorption-compression heat pumps," *Int. J. Refrig.*, vol. 55, pp. 183–200, 2015, doi: 10.1016/j.ijrefrig.2015.02.011.

[29] J. K. Jensen, "Industrial heat pumps for high temperature process applications - A numerical study of the ammonia-water hybrid absorption-compression heat pump," Technical University of Denmark, 2016.

[30] Olvondo Technology, "Olvondo Technology | Make your energy green," 2021. https://www.olvondotech.no/the-technology/ (accessed Jan. 25, 2021).

[31] V. Nair, "HFO refrigerants: A review of present status and future prospects.," *Int. J. Refrig.*, vol. 122, pp. 156–170, 2021, doi: 10.1016/j.ijrefrig.2020.10.039.

[32] Viking Heat Engines, "Contribution to the European energy transition with the world's hottest close loop heat pump," 2019. https://heatroadmap.eu/wp-content/uploads/2019/04/Andreas-Muck_Viking-Heat-Engines.pdf (accessed Jan. 29, 2021).

[33] OCHSNER, "Our business – OCHSNER Wärmepumpen," 2021. https://www.ochsner.com/en/company/ (accessed Feb. 09, 2021).

[34] F. Reissner, B. Gromoll, V. Danov, J. Schaefer, and J. Karl, "Basic Development of a Novel High Temperature Heat," in *Proceedings of 11th IEA Heat Pump Conference 2014*, 2014, pp. 1–12.

[35] F. Reissner, "Development of a Novel High Temperature Heat Pump System," Friedrich–Alexander University Erlangen–Nürnberg, 2015.

[36] DryFiciency, "DryFiciency," 2021. http://dry-f.eu/ (accessed Feb. 15, 2021).

[37] M. ; Bantle, "HeatUp: New high temperature heat pump prototype installed - #SINTEFblog," 2017. https://blog.sintef.com/sintefenergy/new-high-temperature-heat-pump-prototype-installed/ (accessed Feb. 01, 2021).

[38] O. Bamigbetan, T. M. Eikevik, P. Nekså, M. Bantle, and C. Schlemminger, "The development of a hydrocarbon high temperature heat pump for waste heat recovery," *Energy*, vol. 173, pp. 1141–1153, 2019, doi: 10.1016/j.energy.2019.02.159.

[39] B. Zühlsdorf and P. Schneider, “SuPrHeat,” 2021. http://www.suprheat.dk/ (accessed Feb. 15, 2021).

[40] “Strengthening Industrial Heat Pump Innovation Decarbonizing Industrial Heat.”

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High-Temperature Heat Pumps

Electrification of processes and technologies in the Danish industry

22.02.2021

Benjamin Zühlsdorf, bez@dti.dk, +45 7220 1258

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Agenda

- Potential of high-temperature heat pumps
- Technology overview
- Outlook and way forward

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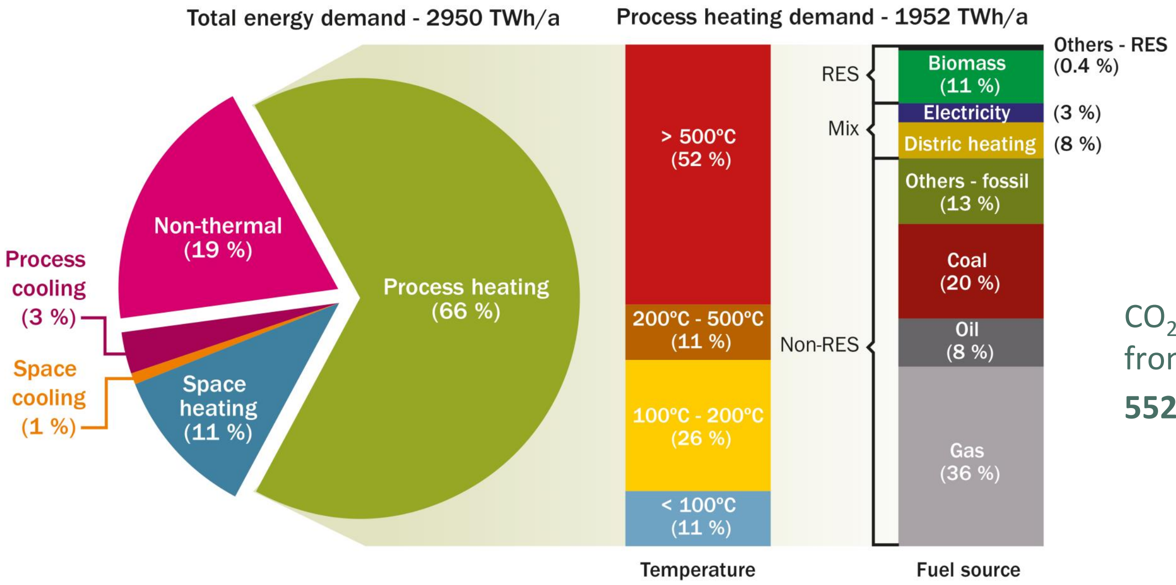
Potential for HTHPs – EU28



CO_2 emissions from Non-RES:

552 Mt/a

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Alternatives for process heat supply

Process

Natural gas
- CO_2 emissions
- Increasing carbon emission taxes

Hydrogen
- Limited roundtrip efficiency
- Suitable for high temperatures

Biomass
- Carbon neutral (if certified)
- Limited availability
- Suitable for high temperatures

Heat Pump
- Highest efficiencies
- Electricity-based and potentially emission free
- Proven principles

Electric boiler
- Limited efficiencies
- Electricity-based and potentially emission free
- Low investment

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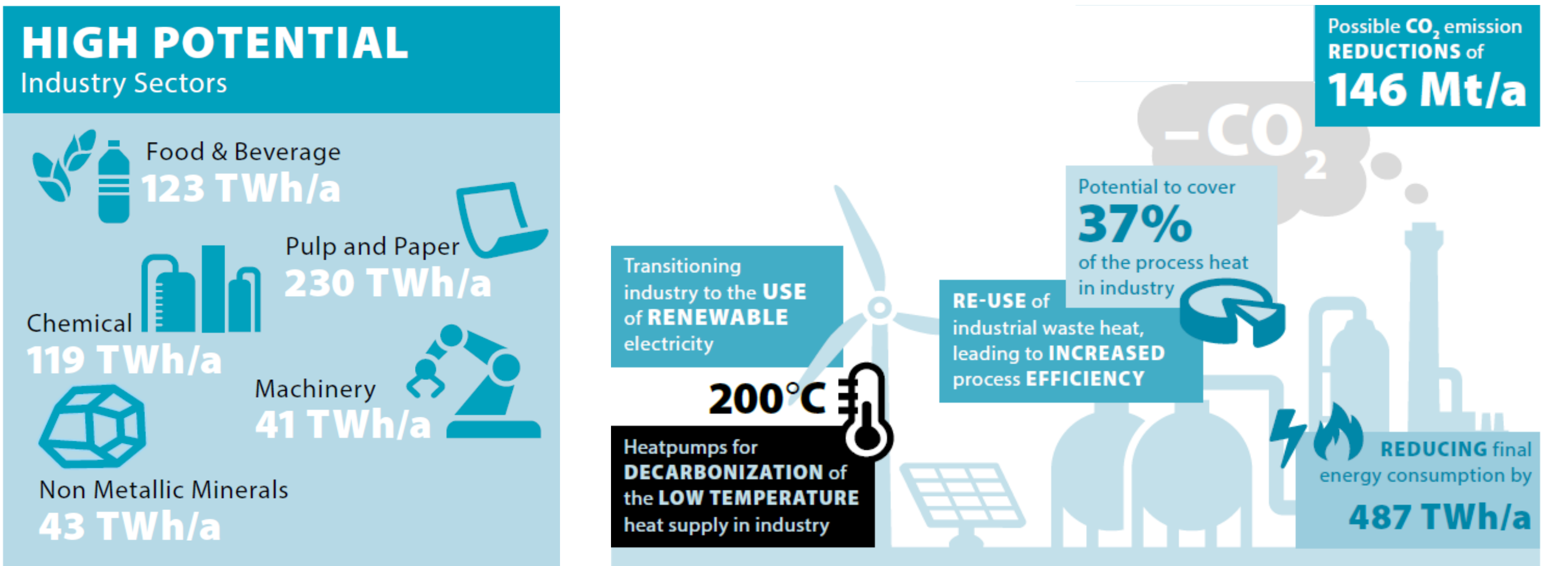

White Paper: *Strengthening Industrial Heat Pump Innovation – Decarbonizing Industrial Heat*

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Potential of industrial heat pumps

Denmark aims for reducing greenhouse gas emissions by 70 % by 2030 compared to 1990.

Klimarådet. *suggests that industry contributes by reductions equivalent to 1.9 mio. tons of CO_2 emissions per year. 0.5 mio. tons per year are to be obtained by "Electrification and heat pumps", mainly implemented between 2025 to 2030.*

Source: "*Kendte veje og nye spor til 70 procents reduktion – Retning og tiltag for de næste ti års klimaindsats i Danmark*", Klimarådet, 03/2020

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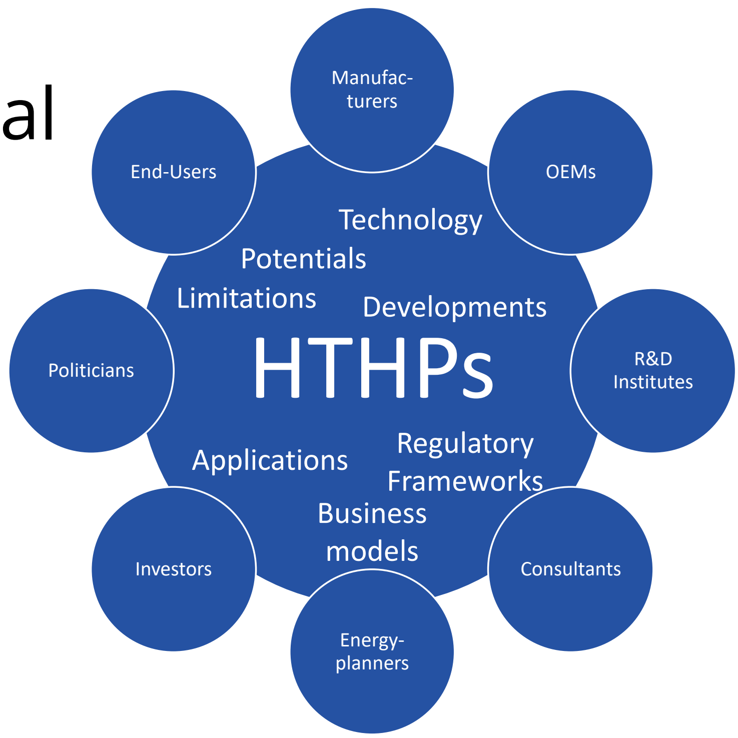
Exploiting the potential

Exploiting the full potential of high-temperature heat pumps requires a common understanding of the **technology**, its **potentials** and its **perspectives** at a variety of stakeholders.



Availability of HTHPs

High-temperature heat pumps are not yet of-the-shelf technology, but there are:

- Limited number of suppliers and products for market ready products
- Close-to-market technologies:
  - Based on proven technology operated at higher temperatures
  - New technology developments
- Suitable (but often expensive) technologies

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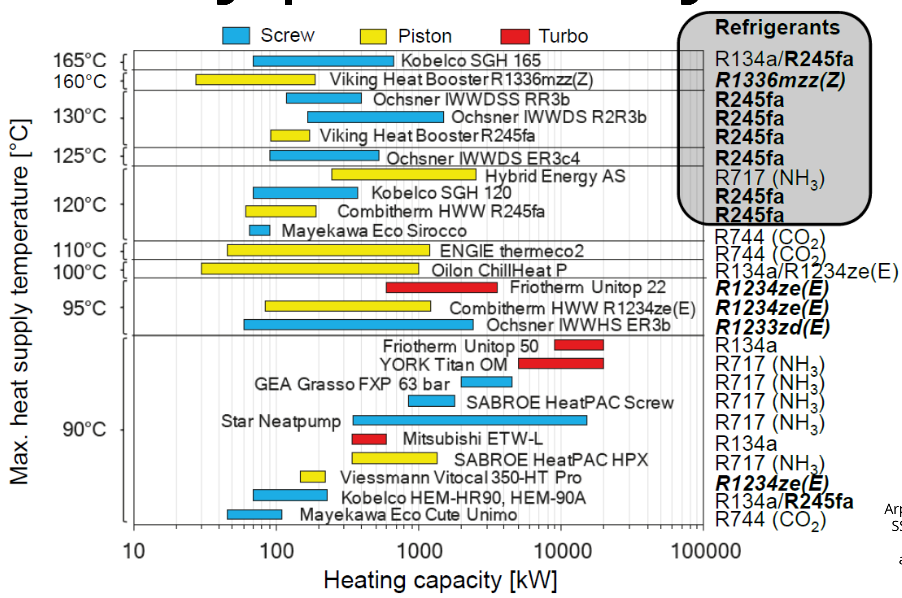
Market ready products by 2018



Arpagaus C, Bless F, Uhlmann M, Schiffmann J, Bertsch SS. High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. Energy 2018;152:985–1010. doi:10.1016/j.energy.2018.03.166.

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Overview of technologies for DK

R718 – Water

- High performances – low pressures – high volume flow rates
- Possible manufacturers
  - Weel and Sandvig – Turbocompressor based on turbocharger
  - Rotrex – Turbocompressor based on turbocharger
  - Spilling – Tailormade piston compressors
  - Piller – Blowers with low pressure ratios
  - ToCircle – Oil-free rotary vane compressor capable of two-phase compression
  - MAN Energy Solutions – Multi-stage integrally geared turbo compressor

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Overview of technologies for DK

Hydrocarbons

- R600 (Butane) for temperatures up to 120 °C
- R601 (Pentane) for temperatures up to 180 °C

- Possible Manufacturers:
  - No manufacturer offers hydrocarbon-specific equipment for high temperatures
  - Various R&D activities are ongoing

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Overview of technologies for DK

R744 – CO_2

- High-pressures – transcritical cycle – well suited for large temperature glides
- Possible manufacturers
  - MAN Energy Solutions – Oil-free turbocompressor based on ETES system with supply temperatures up to 150 °C
  - FENAGY – Supply temperatures of up to 120 °C with large glides
  - ENGIE – Supply temperatures of up to 120 °C with large glides
  - GEA Process Engineering – Integrated equipment for spray dryers with supply temperatures up to 125 °C demonstrated

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Overview of technologies for DK

R717/R718 – Hybrid compression absorption heat pump

- Mixture of ammonia and water – Temperature glide matching
- Possible manufacturers
  - Hybrid Energy/Innoterm – Possible supply temperatures of up to 125 °C, higher supply temperatures possible

R704 (Helium)

- Gas cycle – large temperature glides
- Possible manufacturers
  - Olvondo – Reverse Stirling process, up to 200 °C

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Overview of technologies for DK

HFOs

- Unsaturated HFCs
- Possible manufacturers
  - Viking Heat Engines (insolvent since 2020) – Piston compressors for various HFOs
  - Ochsner – Technologies for HFCs and HFOs up to 130 °C
  - Siemens – Development of HFO heat pump

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Latest R&D projects

- DryF: Demonstration of two technologies in three applications
  - HFO HP, supplying heat at up to 150/160 °C (Brick and Starch drying)
  - Two-stage steam compression for wastewater treatment
- HeatUp: Development of cascade heat pump
  - Propane and butane for supply at up to 115 °C

- Various smaller R&D projects focusing on component developments

SuPrHeat

SuPrHeat
www.SuPrHeat.dk

Motivation
Strong focus on electrification of industry | Increasing competitiveness of HPs
Large heat demand between 100 °C and 200 °C

Objective
Facilitating the electrification of industrial process heat supply at up to 200 °C by development and demonstration of high-temperature heat pumps (3 x 500 kW)

Scope
Technologies: Steam compression, Hydrocarbons, CO_2
Integration and demonstration in dairy, slaughterhouses, breweries and others

Project facts
09/2020 – 08/2024| Budget: 61.3 mio. DKK | EUDP Project
16 Partners: R&D institutes, system manufacturer, OEMs, end-users, consultants

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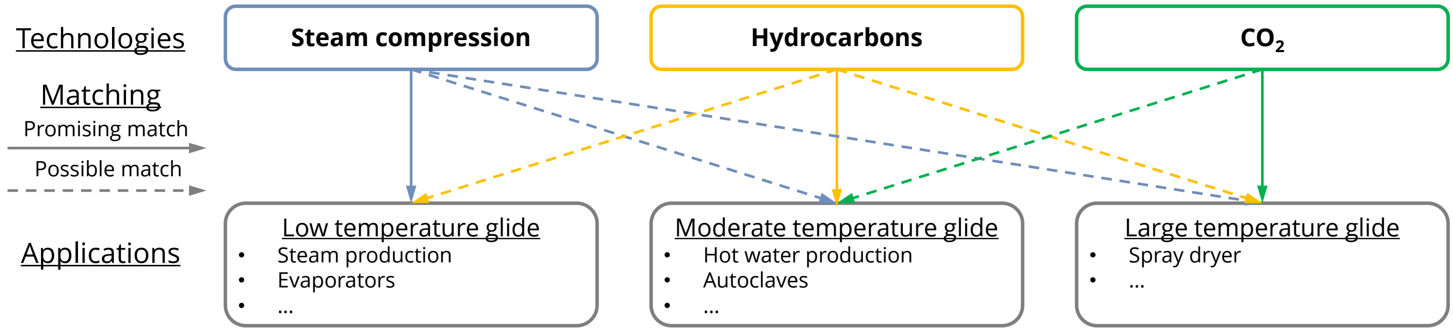
HTHP Concept

SuPrHeat

Development of a concept that covers the majority of processes at highest performances

Suggested concept:



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IEA HPT Annex 58 – HTHPs

Objective

Providing an overview of HP technologies, potentials and perspectives as well as developing concepts and strategies towards HP-based process heat supply

Scope

Heat pump technologies with supply temperatures above 100 °C
Technologies | Concepts | Applications | Testing | Dissemination

Project facts and partner group

01/2021 – 12/2022 | Annex of the IEA HPT TCP
Denmark (Operating Agent)/Austria/Canada/Germany/Norway + potentially Belgium/France/Finland/Italy/Japan/Netherlands/Sweden/Switzerland/UK/US

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Concluding remarks

- High-temperature heat pumps have a considerable potential
- Rapid technology uptake expected for 2025 towards 2030
- Variety of technologies required to provide competitive solutions
- Different (few) technologies are available, but are lacking demonstrations and further R&D
- Further technologies are required
- Knowledge base at various stakeholders to be improved

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The way forward

- Creating a fair regulatory framework that facilitates the acceptance of industrial heat pumps
- Establishing an information and knowledge base to support the integration of industrial heat pumps at all levels of the value chain
- Cutting edge research, development and demonstration projects with industrial heat pumps

White Paper: *Strengthening Industrial Heat Pump Innovation – Decarbonizing Industrial Heat*

Energy Conversion and Management: X 2 (2019) 100011

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Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C

B. Zühlsdorf[a,b,*], F. Bühler[a], M. Bantle[c], B. Elmegaard[a]

[a] Technical University of Denmark, Department of Mechanical Engineering, Nils Koppels Allé, Bygning 403, 2800 Kgs, Lyngby, Denmark
[b] Danish Technological Institute, Energy and Climate, Kongsvang Allé 29, 8000 Aarhus, Denmark
[c] SINTEF Energi AS, Department of Thermal Energy, 7465 Trondheim, Norway

ARTICLE INFO

Keywords:
Electrification
R-718
R-744
Reversed Brayton cycle
Process heat
Steam compression

ABSTRACT

The transition of the manufacturing industry towards carbon neutrality requires a reduction of the emissions from combustion for the supply of process heat. Heat pumps are an efficient alternative technology for supplying heat while improving the overall efficiency and shifting to potentially carbon neutral electricity. The state-of-the-art technology is limited to supply temperatures between 100 °C and 150 °C because of lower efficiency and component limitations. This paper has therefore analyzed two promising concepts for higher supply temperatures and found technically and economically feasible solutions for process heat supply of up to 280 °C. These solutions are using large-scale equipment from oil and gas industries for applications in energy-intensive industries. The suggested systems benefitted from the economy of scale and access to low electricity prices. The concepts outperformed a biogas-based solution, and they were competitive with biomass or natural gas systems with respect to economic performance. It was concluded that an electricity-based heat supply is possible for a wide range of industrial applications and accordingly represents an important contribution to fulfilling the objectives of lower climate impact of energy supply in industry.

1. Introduction

The combustion of fossil fuels for the supply of process heat is becoming unattractive due to increasing fuel costs and CO_2 emission. At the same time, the electricity production from renewable energy sources becomes cheaper [1] and the ratio between cost for electricity from renewables and of fossil fuels decreases [2]. The industry sector of the EU is expected to decrease its greenhouse gas emissions by at least 80 % compared to 1990 until 2050 [3]. Some countries have committed themselves to more thorough strategies. As an example, Denmark aims to be completely independent of fossil fuels by 2050 [4]. This will require significant and fundamental changes in the industry sector, and industries accordingly require alternatives to their current fossil fuel-based energy supply. As a result, the electrification of production processes receives a growing attention.

The *Deep Decarbonization Pathways Project* [5] analyzed different strategies for the practical transition of countries to low-carbon economies. It highlights the beneficial impacts of decarbonizing societies, while enabling growth in economy and population. In relation to the industry sector, improvements in energy efficiency and conservation as well as shifting to emission-free fuels are listed as requirements.

Bataille et al. [6] reviewed the technologies and pathways which enable industries to develop in line with the Paris Agreement [7]. It was outlined that new industrial facilities must be emission-free by 2035 to reach the targets defined in the Paris Agreement. The identified strategy included a general political commitment, followed by local incentives, such as carbon pricing or incentivizing energy efficiency measures, to enhance the market penetration of emission-free or negative emission technologies. The authors further outlined the necessity to bring near-commercial CO_2 emission-free technologies into industries and included heat pumps as alternatives for process heat supply for up to 250 °C.

McMillan et al. [8] analyzed the use of thermal energy in the industrial sector of the US and studied the possibilities to reduce the associated greenhouse gas (GHG) emissions. A large share of the GHG emissions of the industrial sector stemmed directly from fuel combustion for process heat supply and could be reduced by using CO_2 emission-free fuels as well as energy and material efficiency improvements.

The industry in Europe is highly heterogeneous. It represented 25 % of the final energy use in 2015 [9]. The heterogeneity of the industry and the variety of different production methods on a process level enables different degrees of process integration and requires a detailed

* Corresponding author at: Danish Technological Institute, Energy and Climate, Kongsvang Allé 29, 8000 Aarhus, Denmark.
E-mail addresses: bez@dti.dk (B. Zühlsdorf), fabuhl@mek.dtu.dk (F. Bühler), Michael.Bantle@sintef.no (M. Bantle), be@mek.dtu.dk (B. Elmegaard).

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Nomenclature

Abbreviations

CEPCI	Chemical Engineering Plant Cost Index
GHG	Greenhouse gas
HP	Heat pump
HTHP	High temperature heat pump
HX	Heat exchanger
IC	Intercooler
IHX	Internal heat exchanger
TC	Turbocompressor

Variables

A	Area, m^2
c_{alt}	Specific cost per unit heat from alternative supply, €·MWh^{-1}
c_{el}	Specific cost per unit electricity, €·MWh^{-1}
c_h	Specific levelized cost of heat, €·MWh^{-1}
COP	Coefficient of performance, –
COP_{Lor}	Coefficient of performance for Lorenz cycle, –
$COP_{R\text{-}718}$	COP of R-718 multi-stage system, –
$COP_{R\text{-}744}$	COP of R-744 reversed Brayton cycle, –
C_P^0	Purchase cost for equipment at standard conditions, €
CF	Annual cash flow, €·$year^{-1}$
CF_{alt}	Annual income from replacing alternative heat supply, €·$year^{-1}$
CF_{el}	Annual cost for electricity consumption, €·$year^{-1}$
CRF	Capital recovery factor, $year^{-1}$
f_{CEPCI}	Factor to account for the year of the cost function, –
f_{BM}	Bare module factor, –
f_M	Material factor, –
f_P	Pressure factor, –
IRR	Internal rate of return, %
k_i	Factors in cost functions, –
NPV	Net present value, €
OH	Annual operating hours, h·$year^{-1}$
p	Pressure, bar
PBT	Simple payback time, years
$\dot{Q}$	Transferred heat rate, kW
$\dot{Q}_{sink}$	Heat rate supplied to sink, kW
$\bar{T}_{Sink}$	Thermodynamic average temperature of heat sink, K
$\bar{T}_{Source}$	Thermodynamic average temperature of heat source, K
TCI	Total capital investment, €
TCI_{spec}	Specific total capital investment, €
U	Heat transmission coefficient, W·m^{-2}·K^{-1}
$\dot{W}$	Power, kW
$\dot{W}_{comp}$	Compression power, kW
$\dot{W}_{exp}$	Expansion power, kW
X	Scaling parameter in cost functions, see Table 4
ΔT_{lm}	Logarithmic mean temperature difference, K
η_{gear}	Efficiency of gear, –
η_{Lor}	Lorenz efficiency, –
η_{motor}	Efficiency of motor, –

analysis to establish the optimal GHG emission pathways. On the other hand, electrification technologies, applicable to a wide range of industrial processes without requiring major modifications to existing infrastructure would ease the replacement of fossil fuel-based utility systems.

Electric-driven heat pumps have proven to be suitable for supplying process heat in a sustainable and effective way, while improving the overall energy efficiency. Wolf and Blesl [10] conducted numerical studies to quantify the contribution of industrial heat pumps with respect to the mitigation of climate change. Considering state-of-the-art equipment and CO_2 emissions from the German electricity generation mix of 2015, it was found, that reductions of 15 % of the final energy consumption and 17 % of the total energy-related CO_2 emissions could be obtained considering technical constraints only. These potentials reduced to 2.3 % and 4.2 %, respectively, under consideration of economic boundary conditions. A sensitivity analysis revealed a strong beneficial impact of decreasing electricity cost and decreasing investment cost on the profitability of heat pumps. The economically feasible reductions of GHG emission that are obtainable by heat pumps are however expected to increase due to the ongoing decarbonization of the energy sector and decreasing levelized cost of electricity of renewable electricity generation technologies, such as wind and photovoltaic [11]. The electrification is further incentivized by decreasing primary energy factors, which benefit the environmental evaluation of electricity-based heat supply [12].

Heat pumps with sufficient performances are available as state-of-the-art equipment for supply temperatures of up to 100 °C, while different projects demonstrated the technical feasibility of supply temperatures as high as 150 °C to 180 °C, [13,14]. Other studies [15,16] have shown that a relevant heat demand at higher temperatures exists. Among others, material constraints and equipment costs were identified as barriers for industrial high-temperature heat pumps (HTHP) [17]. Increasing the technically feasible supply temperatures of heat pump equipment would further increase the implementation potential and constitute a promising alternative for an efficient and CO_2 emission-free supply of process heat in industrial processes.

State-of-the-art equipment from other sectors, such as chemical processing, might enable the construction of heat pumps exceeding the limitations of heat pumps using equipment originally developed for refrigeration purposes. In order to evaluate these possibilities in more detail, the state of the art is reviewed and potential solutions for heat pump-based process heat supply above 150 °C are identified.

The objectives of this work are i) to demonstrate the techno-economic feasibility of constructing large-scale high-temperature heat pumps for process heat supply, ii) to estimate the environmental and economic potential of the technologies considering different energy supply scenarios in different case studies, and iii) to analyze the potential for applications in different industrial sectors including required actions to exploit this potential.

2. State of the art of heat pumps for supply temperatures above 150 °C

In the literature, different cycles were considered for the supply of process heat at high temperatures. The best cycle for a given application will depend on the framework conditions of the processes, namely the heat sink and source characteristics. In the following, two cycles are introduced and their limitations as well as possible promising applications are discussed. The two cycles that were chosen are a multi-stage cycle using R-718 (water) as refrigerant, which can be constructed as an open or closed system, and a reversed Brayton cycle using R-744 (CO_2) as refrigerant. Both refrigerants are natural refrigerants with a high acceptance in industrial applications.

2.1. Steam compression systems

Steam supply is an established technology for process heating purposes. The steam can be either injected directly into the process or it can be condensed and subcooled in heat exchangers to supply process heat. The direct steam injection corresponds to an open cycle, while the alternative using the heat exchangers is a closed system. Central steam generation units have the advantage of large loads and the possibility to balance the time shift in the demand of different processes, which means extended utilization of the unit. It appears to be promising due to the high utilization of the equipment and low integration cost to consider heat pump-based steam generation systems as an alternative. Kang et al. [18] have reviewed the developments of steam generation heat pumps and analyzed different layouts. They indicated the necessity of further research on the comparison of different technologies using energy, exergy and economic analysis as well as on cascade and multi-stage cycles. They outlined furthermore the demand for research on the compressors for extending the applications to higher temperatures. Bless et al. [19] studied different possibilities for heat pump-based steam generation and outlined the high thermodynamic performances.

The heat pump performance is essentially influenced by the availability of heat sources. Heat sources at sufficiently high temperatures might be directly integrated, while heat sources from lower temperatures can be integrated by means of a bottom cycle. Kaida et al. [20] have analyzed the experimental performance of a system in which steam is generated by a bottom cycle and upgraded to higher pressures by turbocompressors, reaching supply temperatures of 165 °C. Lee et al. [21] studied the suitability of different working fluids for a heat pump, which can be used to produce low-pressure steam or operate as a bottom cycle for a cascade system.

Meroni et al. [22] compared different high-temperature cycles of a cascade heat pump for the generation of steam at 150 °C. The study considered a detailed design of the compressor and found that the direct compression of water in a two-stage cycle outperformed the closed loop cycles using different other working fluids.

Bühler et al. [23] presented a steam generation unit based on a central heat pump that consisted of bottom cycles, supplying heat to a central evaporator at 90 °C while integrating various heat sources, and a high-temperature multi-stage steam compression unit, which supplied steam at different pressure levels to the processes. The presented system had a COP of 1.95 and had the best thermodynamic and economic performance compared to other electrification scenarios that were using decentralized heat pumps and/or electrical heaters.

Various studies have furthermore focused on the analysis of compression equipment that is suitable for the compression of steam. Madsbøll et al. [24] developed a turbocompressor that is suitable to achieve a temperature lift in saturation temperatures of water of 25 K to 30 K at evaporation temperatures of 90 °C to 110 °C. Bantle et al. [25] studied the possibilities to utilize turbocompressors in superheated steam drying applications. Later, Bantle et al. [26] presented experimental tests of a single-stage turbocompressor cycle, which achieved a temperature lift of approximately 25 K. Most recently, Bantle et al. [27] presented an experimental study of a two-stage system. The developed technology was based on mass-produced turbocharger technology from automobile applications. The specific investment costs per unit of supplied heat of systems using this technology were expected to reach values as low as 200 €/kW. Zühlsdorf et al. [28] have shown that steam compressors based on this technology reach economically reasonable sizes for evaporation temperatures above 90 °C to 100 °C. Chamoun et al. [29,30] conducted experiments in a similar operating regime using a twin-screw compressor. While the performance was similar, higher investment cost were expected for the screw compressors. Larminat et al. [31] presented the development and experimental tests for a turbocompressor achieving a temperature lift between saturation temperatures of 90 °C and 130 °C.

These studies demonstrated the technical feasibility of steam compression equipment for supply temperatures of up to 150 °C to 160 °C, while it could be expected that higher temperatures can be achieved with similar equipment. Especially turbocompressors appear to be a promising solution, as they may potentially operate oil-free and

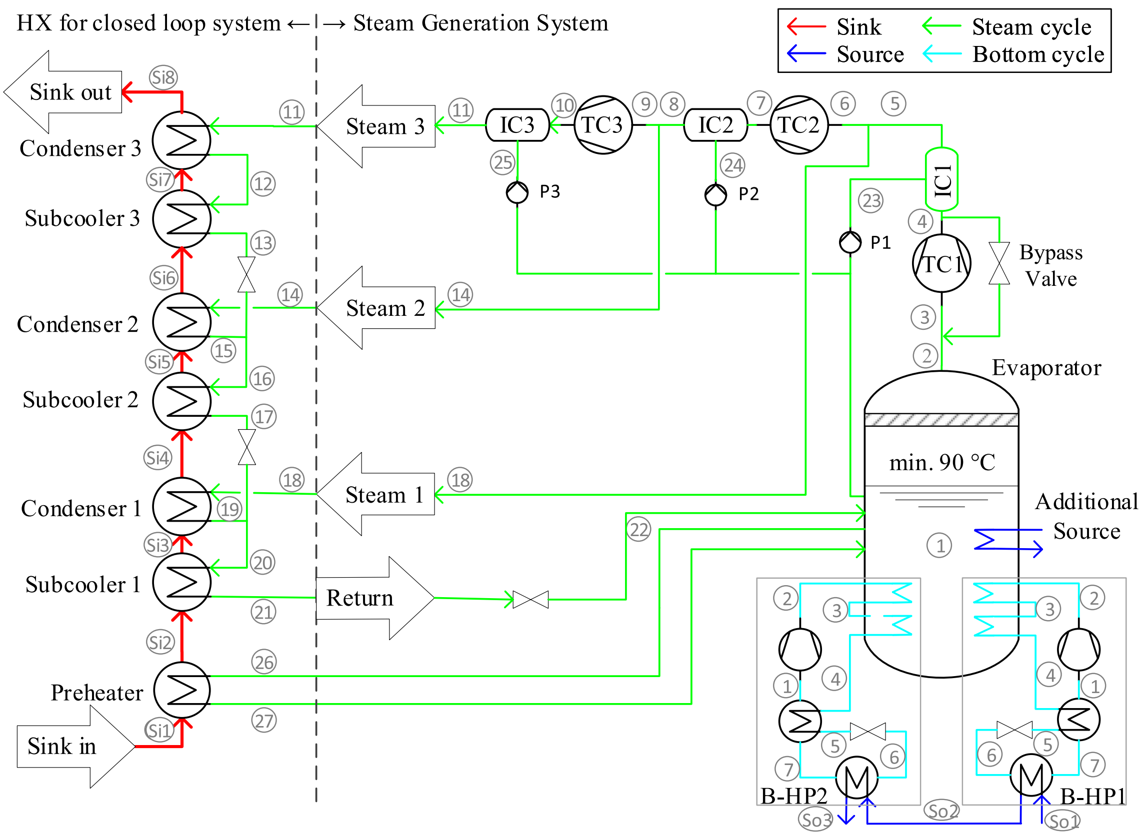

Fig. 1. Flow sheet of a cascade heat pump with a multi-stage R-718 cycle for steam generation or closed loop heat supply at different temperature levels (B-HP = Bottom heat pump, IC = Intercooler, P = Pump, TC = Turbocompressor).

therefore are not limited by current lubrication systems [14]. The obtained pressure ratios per compression stage that could be obtained by turbocompressors reached values of up to 3.5, which is consistent with the expectations from [32,33]. The supplied heat loads achieved in the experimental studies were in the order of up to 1 MW.

While steam compression shows a high efficiency for cases in which both the heat source and sink have relatively constant temperatures with a small glide, it implies inefficiencies when used in applications in which single phase fluids with a certain temperature glide are heated. In such applications, vapor compression cycles using zeotropic mixture [34] or gas cycles [35] might show improved efficiency in cases with larger temperature glides, in which e.g., a single-phase fluid is heated.

2.2. Reversed Brayton cycle

Angelino and Invernizzi [35] reviewed the prospects of reversed Brayton cycles and considered them as a viable alternative for heat supply at high temperatures. Fu and Gundersen [36] presented a method for integrating reversed Brayton cycles in industrial sites and outlined the potential of exploiting the temperature glides in the application.

General Electrics (GE, previously ALSTOM Power) suggested a reversed Brayton heat pump using R-744 (CO_2) in supercritical conditions to be used in a pumped heat electricity storage system [37–39]. R-744 is a natural working fluid with a high industrial acceptance. The storage medium was molten salt in liquid conditions that was heated from 290 °C to 565 °C and stored in tanks. The heat pump used turbocompressors with maximum discharge temperatures that allowed heating the molten salt up to 480 °C, while the remaining temperature lift up to 565 °C was achieved with an electric heater. The heat pump cycle included furthermore an expander that was mounted on the same shaft as the compressor. Considering a heat source at 60 °C, a COP of 1.3 was reported in which only a heat pump was used to supply heat at 465 °C and a combined COP of 1.2, when the temperature was boosted to 565 °C with an electrical heater. During the discharge periods, the molten salt from the hot tank was used to drive a conventional steam power plant.

The heat pump was designed for high-temperature and large-scale applications and utilized large-scale equipment from chemical processes. The maximum scale was constrained by a size of commercially available compressors of 40 MW electrical power. The maximum compressor discharge temperature was found to be high enough to supply a process stream of up to 480 °C while high pressures of up to 140 bar were expected to be feasible. The heat exchangers were assumed to be shell and tube heat exchangers. This highlights that compressors can be found, which are capable of high temperature levels (> 400 °C) and thereby exceed the supply temperatures achieved by compression equipment originating from the refrigeration industry. It may furthermore be noted, that the specific cost of such equipment is decreasing at large capacities, indicating that especially large-scale applications might result in economically feasible solutions.

3. Methods

In the following, the general assumptions for the thermodynamic and economic modelling of the cascade multi-stage steam compression system and the reversed Brayton cycle are introduced. Subsequently, possible applications for large-scale high-temperature heat pumps are determined and case studies for a specific evaluation of the technologies are defined.

3.1. Design of considered heat pump systems

3.1.1. Vapor compression heat pumps using R-718

This work considers a cascade heat pump that was based on the system described [23] and visualized in Fig. 1. The high temperature cycle is a three-stage cycle that supplies heat to the process stream at three different pressure levels and receives subcooled liquid at the temperature of the evaporator from the process. The bottom cycle can consist of one or more cycles in parallel which integrate different heat sources and supply the central evaporator. Heat sources that are available at sufficient temperature can be integrated directly. The cycle was designed to obtain a minimum temperature of 90 °C in the evaporator in order to keep the volume flow rates of the compressors for R-718 at a reasonable level [28]. If a large enough amount of heat is available at higher temperatures, the temperature of the evaporator is increased and no bottom heat pumps are required. In case that bottom heat pumps were required, the evaporator temperature was limited to 125 °C, as this could be covered with state-of-the-art equipment by using e.g., R-600 (butane) [40].

The high-temperature cycle consists of a multi-stage vapor compression cycle using R-718 as working fluid. After each compression stage the steam is desuperheated to 10 K above its saturation temperature by injecting saturated liquid from the evaporator. The three-stage system was designed to achieve maximum supply temperatures of around 210 °C at an evaporation temperature of 90 °C, while it could be extended to higher temperatures by adding more stages in the same manner or increasing the evaporator pressure. The system can be designed as an open system in which the steam is directly injected into the process streams or as a closed system in which the steam is condensed and subcooled before returned to the central evaporator.

In the closed system, the liquid of the high temperature stages is subcooled to the saturation temperature of the next-lowest stage and mixed with the saturated liquid from this stage. Based on the presented literature [32,33], a maximum pressure ratio of 3.5 was assumed and if a higher temperature lift was required, an additional compression stage was considered. The amount of steam supplied to the process at each stage is defined by the application and the system is dimensioned accordingly. All heat demand that occurred below the evaporator temperature was directly covered with liquid condensate, which was returned to the evaporator at subcooled conditions. If the heat demand was required at temperatures that were too high for cooling the liquid to the evaporator temperature, it was flashed into the evaporator tank.

Table 1 summarizes the assumed component efficiencies for the numerical modelling. The isentropic efficiency and the maximum pressure ratio were chosen in accordance with [27,28,32]. No pressure drops and heat losses within the piping and the heat exchangers were considered for the simulations. In a closed system, the liquid was sufficiently subcooled to the temperature of the evaporator, while the liquid feed was accordingly heated by an auxiliary heat pump for an open system. The evaporator was assumed to be ideally mixed, while no pumping power was considered.

The thermodynamic performance of the steam cycle was evaluated by its $COP_{R\text{-}718}$. The $COP_{R\text{-}718}$ was defined as the ratio of the supplied heat $\dot{Q}_{sink}$ to the total power consumed $\dot{W}_{total}$. The total power consumption comprised the sum of the compressor power $\sum \dot{W}_{comp}$ of the different compressors from the bottom and the high-temperature cycle as well as the power of all pumps $\sum \dot{W}_{pump}$ under consideration of an efficiency for the motor η_{motor} and the gear η_{gear}. The supplied heat load $\dot{Q}_{sink}$ assumed that the steam is in both cases subcooled to the evaporator temperature and completely used for process heating purposes. If heat was covered by using the saturated liquid from the evaporator,

Table 1
Modelling assumptions for steam compression heat pump.

Isentropic efficiency compressor	75 %
Efficiency of pumps	90 %
Efficiency of motor η_{motor}	95 %
Efficiency of gear η_{gear}	95 %
Maximum pressure ratio per stage	3.5
Remaining superheat after liquid injection	10 K

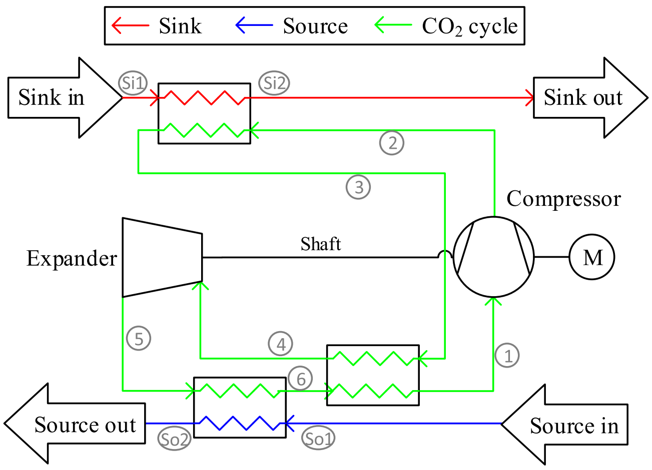

Fig. 2. Flow sheet of reversed Brayton cycle.

this was considered as well.

$$COP_{R-718} = \frac{\sum \dot{Q}_{sink}}{\dot{W}_{total}/(\eta_{motor}\eta_{gear})} \quad (1)$$

The bottom heat pump cycles were modelled as described in [41,42]. The compressor was modelled with an isentropic efficiency and the expansion process assumed to be isenthalpic. The pressure levels and the subcooling were defined by minimum pinch point temperature differences. The transferred heat in the internal heat exchanger was maximized, as this yielded the maximum COP, while a minimum pinch point temperature difference was respected. The efficiencies for the compressor, the gear and the drive were assumed as for the high-temperature cycle. The heat exchangers were modelled with separate sections in which the refrigerant was in either liquid, gas or two-phase conditions. It was however assumed that the evaporator and the superheater as well as the desuperheater and condenser were manufactured as one component. Considering that all thermodynamic state points were defined, the mass flow rates were determined by mass and energy balances in order to meet the process heat demands.

3.1.2. Reversed Brayton cycle

Fig. 2 shows the layout of the considered reversed Brayton cycle. The compressor was also in this case a turbocompressor. It was mounted on the same shaft as a turbine that recovers the expansion work. The recovery of expansion work appeared promising due to the high pressure ratios and since expansion occurred in the gas phase. Recovering the expansion work was not considered in the multi-stage R-718 cycle, as the thermodynamic potential was smaller and since the expansion was located within the two-phase zone. Further, an internal heat exchanger was considered to cool the working fluid subsequent to the gas cooler while heating the stream in front of the compressor.

Table 2 summarizes the modelling inputs. The isentropic efficiencies of the turbomachinery are dependent on the specific working conditions and the capacity, while conservative estimates based on e.g., [35], were assumed for this study. No pressure drops or heat losses from the piping or the heat exchangers were considered. The pressure levels were optimized with respect to a maximum COP, while the pressure was constrained to a maximum of 140 bar. The outlet conditions of the turbine were a design parameter and they were optimized to be at least 5 K above the corresponding saturation temperature. The definition of the turbine outlet temperature indirectly determined the pinch point temperature difference and thereby the size of the internal heat exchanger. The mass flow rate was determined by the heat load required by the process.

Table 2
Modelling assumptions for reversed Brayton cycle.

Isentropic efficiency compressor	75 %
Isentropic efficiency turbine	75 %
Efficiency of motor η_{motor}	95 %
Efficiency of gear η_{gear}	95 %

The $COP_{R\text{-}744}$ was determined as the ratio of the supplied heat $\dot{Q}_{sink}$ to the difference of the compressor power $\dot{W}_{comp}$ and the expander power $\dot{W}_{exp}$ under consideration of an efficiency for the motor η_{motor} and the gear η_{gear}.

$$COP_{R-744} = \frac{\dot{Q}_{sink}}{(\dot{W}_{comp} - \dot{W}_{exp})/(\eta_{motor}\eta_{gear})} \quad (2)$$

3.2. Thermodynamic evaluation

In order to evaluate the efficiency of the cycles, the COPs were related to the maximum achievable COP of a theoretical cycle. The Lorenz cycle [43] is a theoretical cycle with an isentropic compression and expansion process and heat transfer at the thermodynamic average temperatures [44] of the heat source $\bar{T}_{Source}$ and the heat sink $\bar{T}_{Sink}$. The performance of the Lorenz cycle is described by the COP_{Lor}.

$$COP_{Lor} = \frac{\bar{T}_{Sink}}{\bar{T}_{Sink} - \bar{T}_{Source}} \quad (3)$$

The Lorenz efficiency η_{Lor} describes the efficiency of the respective cycle by relating the COP to the Lorenz COP_{Lor}.

$$\eta_{Lor} = \frac{COP}{COP_{Lor}} \quad (4)$$

3.3. Economic evaluation

In order to evaluate the economic performance, the investment costs as well as the operating costs need to be calculated. For the estimation of the investment costs, the component dimensions of the main components were determined before the capital costs were estimated using correlations. The capital costs were subsequently compared to the operating cost under consideration of the time value of the money for different representative cost scenarios.

3.3.1. Component dimensioning

The estimation of the capital cost of the equipment requires an estimation of the component dimensions for the main components of the system. The component costs were estimated based on parameters describing the components capacity or dimensions. For some of the components, such as the compressors, turbines and drives, the capacity was described by the power, which was directly available from the thermodynamic calculations. The capital costs for heat exchangers was determined based on their area.

The relation between the required area A and the transferred heat $\dot{Q}$ for a heat exchanger in which two streams of constant capacities are exchanging heat was described by Eq. (5) [44]. The heat exchangers were discretized in sufficiently small parts of equal heat transfer to allow the assumption of constant capacities.

$$\dot{Q} = UA\Delta T_{lm} \quad (5)$$

The UA-value was determined by the logarithmic mean temperature difference ΔT_{lm}. In order to determine the area A from the UA-value, the heat transmission coefficient U was estimated. The heat transmission coefficient U considers the heat transfer coefficients on both sides of the heat exchangers. Dependent on the design of the heat exchangers and the involved fluids, a range of heat transfer coefficients can be achieved for technically feasible and economically reasonable heat exchanger designs. The heat transfer coefficients considered in this study were estimated based on the experience-based values from [45]. Table 3 summarizes the heat transfer coefficients, the components and

Table 3
Assumptions for the heat exchanger selection and dimensioning dependent on the involved process streams.

Side 1	Side 2	Heat exchanger type	Minimum pinch point temperature difference, K	Heat transfer coefficient, U Wm^{-2}K^{-1}
Gas (e.g., air)	Working fluid (liquid)	Shell & tube HX	7.5	42.5
	Working fluid (gaseous)	Shell & tube HX	7.5	40.0
	Working fluid (condensing)	Shell & tube HX	7.5	42.5
	Working fluid (evaporating)	Shell & tube HX	7.5	42.5
Liquid (e.g., water)	Working fluid (liquid)	Shell & tube HX	5.0	750.0
	Working fluid (gaseous)	Shell & tube HX	5.0	42.5
	Working fluid (condensing)	Shell & tube HX	5.0	1000.0
	Working fluid (evaporating)	Shell & tube HX	5.0	1000.0
Working fluid (evaporating)	Working fluid (condensing)	Evaporator vessel with internal coils	5.0	1250.0
Working fluid (gaseous, high pressure)	Liquid (e.g., thermal oil)	Shell & tube HX	7.5	150.0
	Working fluid (gaseous)	Shell & tube HX	7.5	70.0

the minimum pinch point temperature differences that were used in this study depending on the involved streams.

3.3.2. Component cost estimation

The purchase cost for the components in base conditions, meaning basic material at standard operating conditions without auxiliary equipment, C_P^0, was determined by a cost function as described in Eq. (6) [46,47]. The parameters that were used for these cost functions are summarized in Table 4 and were taken from the same literature.

$$\log(C_P^0) = k_1 + k_2\log(X) + k_3(\log(X))^2 \quad (6)$$

The bare module cost of the equipment C_{BM} includes both the direct and indirect cost related to the component. The cost for auxiliary materials, labor and engineering is summarized by the bare module factor f_{BM}. The additional cost for the design of the equipment in different material and to operate at increased pressures are estimated by the factors f_M and f_P, as defined in [46,47]. A pressure factor $f_P = 1.2$ was assumed for the construction of the heat exchangers at the high pressure side of the R-744 cycle.

$$C_{BM} = f_{BM} f_P f_M f_{CEPCI} C_P^0 \quad (7)$$

As the cost functions were reported in different years, the cost estimations were converted to values corresponding to the year 2017 by the factor f_{CEPCI}, which was based on the Chemical Engineering Plant Cost Index (CEPCI).

Based on the bare module cost of the components, the total component costs can be estimated by considering a factor of 18 %, accounting for possible contingencies and fees [46]. The costs for integrating the unit on site and retrofitting an existing plant, an additional factor of 15 % was considered, yielding the total capital investment cost TCI. In order to compare the TCI of different solutions, the specific total capital investment was expressed as in relation to the supplied heat load TCI_{spec}. To account for the non-energy related operation and maintenance costs, an additional 20 % of the TCI was used as a one-time payment.

3.3.3. Economic performance indicators

The net present value NPV was chosen for the evaluation of the economic performance of the different solutions, as it is an indicator that considers the entire lifetime of the plant [44,47,48]. The NPV considers both the total capital investment cost TCI and the summed cash flows for each year CF. The cash flows were expected to be constant throughout the lifetime and were converted to their time value at the time of the investment by the capital recovery factor CRF. The CRF considered an effective interest rate of 5 % and a lifetime of the plant of 20 years.

$$NPV = -TCI + \frac{\sum CF}{CRF} = -TCI + \frac{CF_{alt} - CF_{el}}{CRF} \quad (8)$$

The levelized specific cost of heat c_h was considered as another measure for the comparison of the alternatives. It relates the investment cost corresponding to one year of operation TCI·CRF and annual operating cost due to consumption of electricity or another fuel $\sum CF$ to the annually supplied heat $OH \cdot \sum \dot{Q}_{sink}$.

$$c_h = \frac{TCI \cdot CRF}{OH \cdot \sum \dot{Q}_{sink}} + \frac{\sum CF}{OH \cdot \sum \dot{Q}_{sink}} \quad (9)$$

The simple payback time PBT was introduced as a measure for the estimation of the uncertainties associated with the investment, by determining the period which is required until the profit compensated the total capital investment without considering the time value of the cash flows. The payback time is however insufficient for the evaluation of the profitability of the investment, as it only considers part of investments lifetime [44,47,48].

$$PBT = \frac{TCI}{CF_{alt} - CF_{el}} \quad (10)$$

As an additional indicator the internal rate of return IRR [44] was used, which is defined as the interest rate at which the NPV of the investment equals zero.

The sum of the annual cash flows represents the annual savings that would result from substituting the existing energy utility with the suggested system. The cash flow resulting from the electricity consumption in the considered scenario CF_{el} was determined by the sum of the consumed power $\sum \dot{W}$, the annual operating hours OH and the specific electricity cost c_{el}. The cash flow describing the savings for substituting the alternative heat supply CF_{alt} was defined by the amount of the supplied heat $\sum \dot{Q}_{sink}$, the operating hours OH and the specific cost for the alternative heat supply c_{alt}.

$$CF_{el} = c_{el} OH \sum \dot{W} \quad (11)$$

$$CF_{alt} = c_{alt} OH \sum \dot{Q}_{sink} \quad (12)$$

Both the specific cost for the alternative heat supply and the electricity consumption are effective costs, meaning that they are including the net price, additional fees and taxes and in case of the alternative heat supply also the boiler efficiency. The following section discusses the different scenarios and presents the considered costs.

3.3.4. Scenarios for the economic and environmental evaluation of the case studies

This section defines economic and environmental scenarios for the evaluation of the case studies, which are summarized in Table 5. The heat pumps can be based on electricity supply from the grid or from

Table 4
Parameters for estimation of component capital cost.

Component	Scaling parameter *X*	Range	k_1	k_2	k_3	Year	f_{BM}	Ref.
Centrifugal/reciprocating compressors	Fluid power	450 kW – 3000 kW	2.2897	1.3604	−0.1027	2001	2.8	[46]
Drive (electric, totally enclosed)	Shaft power	75 kW–2600 kW	1.9560	1.7142	−0.2282	2001	1.5	[46]
Evaporator plain vessel	Volume	$1\ m^3 - 800\ m^3$	3.5970	0.2163	0.0934	2004	3.0	[47]
Internal coils in evaporator tank	Area	$1\ m^2 - 8000\ m^2$	3.2195	0.3743	0.046	2004	1.0	[47]
Screw compressors	Fluid power	10 kW – 1000 kW	3.4756	0.6814	$-8\cdot10^{-6}$	2004	2.2	[47]
Shell & tube heat exchanger	Area	$10\ m^2 - 900\ m^2$	3.2476	0.2264	0.0953	2004	3.2	[47]
Turbine (radial)	Fluid power	100 kW–1500 kW	2.2476	1.4965	−0.1618	2001	3.5	[46]

own renewable electricity production facilities. The electricity prices and the associated CO_2 emissions are varying according to the local electricity markets, electricity mix and taxes. The analysis was based on data from three countries, which were selected as exemplifying scenarios. Germany was chosen as it has a large and diverse industrial sector and a large share of fossil fuel-based electricity production, while Denmark has a large share of renewable electricity from wind and Norway from hydro. The share of electricity production from wind, solar and hydro accounted for 97.6 % in Norway and for 46.6 % in Denmark in 2016 [49]. The cost scenarios that were selected for these countries corresponded to the most favorable conditions, which are typically limited to customers with consumption in the range of energy-intensive industries. It may be noted that customers with lower electricity demands may be paying higher prices. The selection of the ambitious electricity prices was however based on the assumption, that the industries with access to the lowest electricity tariffs will be the first ones for which the installation of heat pumps will become beneficial. It was furthermore expected that the installation of the suggested heat pump systems increases the electricity consumption to a considerable extent, which may give access to lower electricity tariffs.

Philibert [11] emphasizes the possibility for energy-intensive industries to invest directly in renewable electricity production facilities. An additional scenario was added. It was assumed that only electricity from wind and solar is accepted and that the industry itself acquires and operates the electricity generation. It is expected that the levelized cost of electricity from renewables can become as low as 30 €/MWh, depending on the location and combination of different technologies [1,11]. Based on [50,51] and assuming Danish conditions, the levelized cost of electricity in 2020 is expected to range from 30 €/MWh for onshore wind energy to 47 €/MWh for offshore wind, with nearshore wind energy and large photovoltaic at 41 €/MWh. Additional costs are expected for storage facilities and measures to operate the local electricity grid. For this study, an average levelized cost of electricity of 40 €/MWh was assumed, with a potential range of 30 €/MWh to 50 €/MWh.

The heat pump technologies were evaluated for the aforementioned scenarios and were compared to different technologies. As potential alternative technologies, an electrical boiler and different combustion-based boilers were considered. Natural gas, biogas and biomass were considered as fuels for the combustion-based boilers. The specific cost including taxes for natural gas was 27.7 €/MWh for Norway [52,53], 28.7 €/MWh for Denmark [54–56] and 33.1 €/MWh for Germany [2]. For this study, a range of 28 €/MWh to 33 €/MWh was assumed. The installation of a natural gas boiler was associated with a specific investment cost of 103 €/kW of heating capacity [56]. The specific cost for biomass was assumed to be in the range of 64 €/MWh for normal biogas and 75 €/MWh for upgraded biogas [57]. The investment cost for the gas boiler for biogas was assumed to be the same as for natural gas. The market price of biomass was assumed to be in the range of 28 €/MWh for wood chips and 33 €/MWh for wood in Denmark in 2020 [58]. The investment cost for biomass boilers including storage facilities was assumed as 800 €/kW of heating capacity [56].

The specific scenarios are summarized in Table 5. It includes the specific fuel cost, specific CO_2 emissions and the potential technologies. The specific CO_2 emissions of natural gas were assumed as 0.204 t/MWh [59], while they were assumed to be zero for biogas and biomass. The combustion of biomass and biogas might however be subject to a NO_x-tax as it is in Denmark [54].

3.4. Evaluation of the application potential of heat pump-based process heating at high temperatures

In order to identify industries and processes where high temperature heat pumps can have a promising application potential, industrial sectors were evaluated as a basis for the selection of case studies for a deeper analysis of the technical and economic potential.

The evaluation criteria for promising applications were industrial processes where (i) heat is required at temperatures between 150 °C and 450 °C, (ii) heat is typically supplied from external sources (e.g., steam from boilers, combustion heat) and not internally (e.g., from exothermic reactions or through process integration), (iii) the heat demand is high (above 1 MW) and (iv) heat is required continuously and with a high number of annual operating hours.

3.4.1. Identification of promising industrial sectors

Several studies analyzed the industrial process heat demand and excess heat including the temperature ranges on industry sector level for different countries. Naegler et al. [60] quantified the industrial heat

Table 5
Considered fuels and potential technologies for 2020 conditions.

Fuel		Fuel price incl. taxes, €/MWh			Specific CO_2 emissions, kg/MWh	Potential technologies
		Chosen value	Lower range	Upper range		
Electricity	Denmark [55–57]	63.1	–	–	461	- Reversed Brayton cycle
	Germany [2]	52.1	–	–	624	- Steam Compression cycle
	Norway [53,54]	36.1	–	–	570	- Electric boiler, η = 0.95, TCI_{spec} = 210 €/kW
	Renewable [1,11]	40.0	30.0	50.0	0	
Natural Gas [55–57]		31.0	28.0	34.0	204	- Gas boiler, η = 0.9, TCI_{spec} = 103 €/kW
Biogas [46,56,57]		69.5	64.0	75.0	0	
Biomass [2,46,57]		30.5	28.0	33.0	0	- Biomass boiler, η = 0.9, TCI_{spec} = 800 €/kW

demand on a European level. Based on data for Germany the share of process heat demand in the range of 100 °C to 500 °C was found to be highest in the chemical, food, paper and construction industry, where the share was between 20 % and 70 % of the total heat demand of the respective sector. While the share of process heat demand between 100 °C and 500 °C was approximately 20 % of the industrial heat demand in the largest industrial heat user countries, it was above 30 % in Sweden, Finland and Portugal.

Rehfeldt et al. [61] also analyzed industrial processes in Europe using bottom-up estimates and similarly found that the pulp and paper, food and beverages and chemical industry have the highest heating demands in the range of 100 °C and 500 °C, but also the processing of non-metallic minerals was found to have a high heat demand in this range. The distribution of process heat demand among European countries was found to vary. On average 40 % of process heat is required above 500 °C, the heating demand between 100 °C and 500 °C was 30 % but in some countries (e.g., Finland, Sweden, U.K. and Austria) it was considerably higher. The processes accounting for the major share of the heat demand in the temperature range between 200 °C and 500 °C were secondary aluminum production and rolling/extruding of aluminum, flat glass, gypsum and ethylene production. A majority of the energy use in food, beverage, pulp and paper industries was found in the temperature range between 100 °C and 200 °C.

McKenna and Norman [62] analyzed heating demands for industrial sectors and the recovery potential for excess heat for the UK. The pulp and paper, food and drink and chemical industry sectors were found to have the majority of its heat demand between 100 °C and 500 °C. The heating demand in this temperature range accounted for 160 PJ, out of a total heat demand of 788 PJ. The recovery potential of heat was estimated to be between 37 PJ and 73 PJ per year [63].

Arpagaus et al. [14] analyzed different heating demands based on literature data, to identify the potentials for heat pumps with supply temperatures up to 140 °C. For Germany the potential of process heat which is coverable by heat pumps with sink temperatures between 80 °C and 140 °C was estimated to be 337 PJ. The main processes for high-temperature heat pump application were identified in drying, pasteurizing, sterilization, evaporation and distillation processes.

The pulp and paper industry has a large potential for energy efficiency, where heat recovery and integration presents the largest CO_2 mitigation potential at the lowest specific costs [64]. The use of heat pumps is an important approach in obtaining a high level of energy efficiency, however the process temperatures are typically below 150 °C where heat pump technologies are available [65]. This sector is therefore not further considered in this study for the use of HTHP.

Based on these findings, the following industrial sectors were identified as sectors, in which the presented technologies were expected to potentially be able to increase the temperature limits for process heat supply to above 150 °C, while yielding economically feasible performances:

- Chemical and petrochemical industry
- Ferrous and non-ferrous metal industry
- Non-metallic minerals industry
- Food and beverage industry

3.4.2. Case studies

Two case studies were defined to analyze the energetic, environmental and economic performance in more detail. The case studies were chosen representing possible applications from the aforementioned industries. Based on the case study results, the potential for further applications in these industries is discussed.

3.4.2.1. Case study of alumina production. The aluminum production has a high energy intensity, which results in an accordingly high rate of CO_2 equivalent emissions [66] and accounts for a high share of the final product costs [67]. A large share of the energy is consumed during the refining of bauxite to alumina, which is a basic material for the aluminum production [68]. The Bayer process is the most established process for the refining of bauxite and the largest share of the energy is required as heat for preheating and digesting the bauxite, while the maximum temperatures vary between 140 °C and 280 °C, depending on the quality of the bauxite, the utilized equipment and various other factors [67].

The heat for preheating and digesting the bauxite slurry can be supplied by steam or by single-phase fluid, e.g., molten salt or a thermal oil [69–71]. Steam can be injected directly, while the single-phase fluids require heat exchangers for indirect heat exchange. The latter results in larger temperature differences but higher energy efficiencies [72].

As the entire process is energy-intensive, there is a high availability of excess heat at sufficient temperatures, which could potentially be utilized as a heat source of a heat pump. A suitable heat source could e.g., be the exhaust air from the calcination stage [73].

For the evaluation and comparison of the heat pump technologies, a representative case study was defined, corresponding to potential conditions as described by the aforementioned literature. It was assumed that heat is supplied to a stream of constant heat capacity flow rate, e.g., thermal oil or a molten salt, which is heated from 140 °C to 280 °C, while heat is taken from excess heat from another on-site process between 110 °C and 60 °C. The required heat load was defined as 50 MW, as this corresponds to typical plant sizes and approximately to the largest commercially available compressors for the reversed Brayton cycle [37]. The mass flow rate of the source was determined by the system COP. The annual operating hours were assumed as 8000 h/year.

3.4.2.2. Case study of a spray drying facility. Spray drying facilities in the food industry are typically accounting for a large portion of the energy use of the sector and represent some of the highest process temperatures. Spray dryers are furthermore often in the range of several megawatts capacity and often operate throughout the year. This makes them a promising application for a heat pump-based process heat supply. In spray dryers, the liquid is atomized and sprayed into a drying chamber with heated air [74]. The droplets of food move with the heated air and the water evaporates.

In this study, we considered a spray drying facility based on the milk production site for which Bühler et al. [75] conducted an energy, exergy and advanced exergy analysis. Zühlsdorf et al. [34] studied the integration of heat pumps with zeotropic mixtures for the same spray drying facility. They presented a heat pump solution to preheat the drying air to 120 °C, which decreases the natural gas consumption by 36 %. Bühler et al. [23] compared further different strategies for the design of a fully electrified production system. After the integration of direct heat recovery, the inlet air with a mass flow rate of 54.9 kg/s and a humidity of 6.43 g/kg had to be preheated from 64 °C to 210 °C, while the outlet air with a mass flow rate of 64.3 kg/s and a humidity of 28.88 g/kg at a temperature of 50 °C could be used as heat source. The amount of heat recovered from the heat source, and accordingly the outlet temperature, were determined by the system COP. The annual operating hours were assumed to be 7000 h/year.

4. Results

The Brayton cycle and the steam compression unit were evaluated for two case studies under consideration of the different economic and environmental boundary conditions. The main technical parameters of the two concepts for the two case studies are presented in the following, before the economic analysis is presented and the potentials of the technologies for other industries are discussed.

4.1. Technical concepts for the case studies

4.1.1. Multi-stage steam compression cycle (R-718)

The steam compression cycles for both applications were designed with 3 compression stages. The two low-pressure stages were chosen with a pressure ratio of 3.2, while the pressure ratio of the third stage was 2.84 for the alumina production case study and 3.03 for the spray dryer case study. The overall COP was 1.9 for both cases, which corresponds to a Lorenz efficiency of 49 %.

Fig. 3 shows the temperature-heat diagram and Fig. 4 the logarithmic pressure-enthalpy diagram for the steam compression cycle for the alumina production case. The heat sink inlet temperature was 140 °C, and the evaporator temperature was chosen to be 125 °C, as it could be supplied by a bottom heat pump using butane (R-600) [40]. The evaporator pressure was 2.3 bar and the condensing pressures of stage 1, 2 and 3 were 7.4 bar, 23.8 bar and 67.5 bar and the compressor outlet temperatures 302 °C, 355 °C and 397 °C, respectively. The compressors were of 5.8 MW, 5.6 MW and 3.4 MW shaft power capacity. The COP of the R-718 steam compression cycle was 3.0.

The two bottom heat pumps were single stage heat pumps with an internal heat exchanger using R-600. The capacities of the heat pumps were chosen to recover an equal amount of heat of each 12.8 MW from the heat source while supplying a total amount of 34.9 MW to the evaporator of the high temperature cycle. The first heat pump cycle operated with an evaporation pressure of 9.6 bar and had a COP of 4.2, while the second bottom heat pump had an evaporation pressure of 5.3 bar and a COP of 2.9. The condenser pressure was 26.3 bar in both cases.

Both bottom cycles were designed with a maximum internal heat exchange, as this yielded the maximum COP. This did however also result in a large amount of desuperheating, which might imply larger volume flow rates, a larger pressure drop and a large temperature gradient in the desuperheater.

Fig. 5 shows the temperature-heat-diagram for the multistage steam compression cycle for the spray dryer case. In this case, the sink inlet temperature was below 90 °C, which was defined as the minimum evaporation temperature with respect to reasonable compressor volume flow rates [28]. This enabled that the first part of the stream could be preheated by direct heat transfer using liquid from the evaporator holdup. The evaporation pressure was 0.7 bar, while the pressure in the condensers were 2.2 bar, 7.2 bar and 21.8 bar. The compressors had a shaft capacity of 0.8 MW, 0.6 MW and 0.4 MW and outlet temperatures of 257 °C, 301 °C and 344 °C for stage 1, 2 and 3, respectively.

Also for the spray dryer case, two bottom heat pump cycles with an internal heat exchanger using R-600 were chosen. In this case, the heat

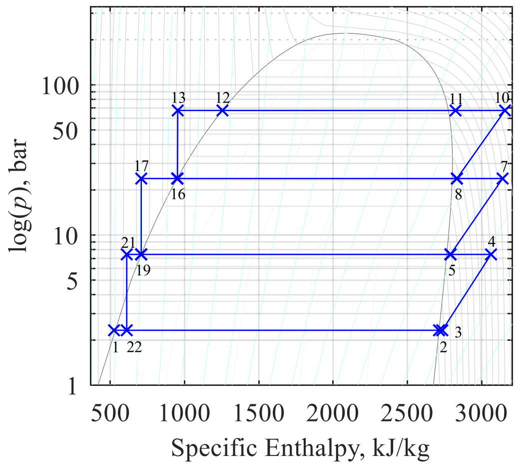

Fig. 4. Logarithmic pressure-enthalpy-diagram for the R-718 top cycle of the heat pump for the alumina production case study with selected state point numbers indicated.

source was moist air and the first heat pump was designed to recover the heat until the dew point of 31 °C while the second heat pump cycle recovered the remaining heat including the condensing heat of the moist air. The first heat pump had an evaporation pressure of 2.3 bar and recovered 1.3 MW with a COP of 3.1. The second cycle had an evaporation pressure of 1.6 bar and recovered 3.0 MW from the condensing moist air with a COP of 2.7. Both bottom cycles had a condenser pressure of 13.7 bar. Due to the flexibility of designing the bottom heat pump cycles according to the heat source characteristics, the condensing heat of the moist air could be efficiently recovered.

4.1.2. Reversed Brayton cycle (R-744)

Fig. 6 shows the temperature-heat-diagram and Fig. 7 the temperature-entropy-diagram for the reversed Brayton cycle for the boundary conditions of the alumina production case study. The optimal pressures were 40.7 bar at the low pressure side and 140 bar at the high pressure side, which corresponds to a pressure ratio of 3.4. The outlet temperature of the compressor was 290 °C, The COP of the cycle reached 1.72, which was slightly lower than 1.92 as obtained for the steam compression cycle. The cycle performance corresponds to a Lorenz efficiency of 44 %.

It may be noted that the temperature profiles of the heat exchangers were matching well in all heat exchangers, indicating a small amount of irreversibility during heat transfer. The pinch point in the heat source heat exchanger occurred at the source inlet, indicating that a higher

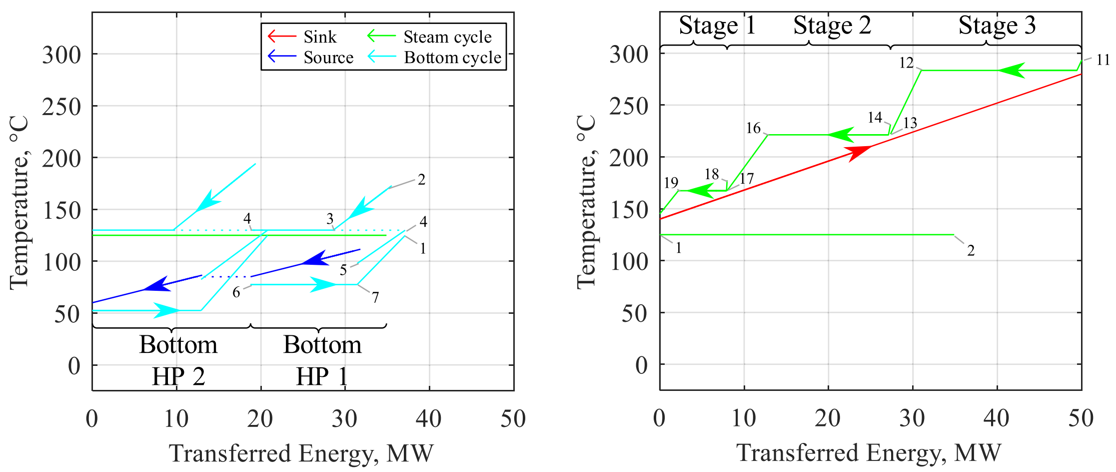

Fig. 3. Temperature-heat-diagram for the bottom cycles using R-600 (left) and the multi-stage top cycle using R–718 (right) for the alumina production case study. Selected state point numbers are shown for the bottom HP 1 and for the multi-stage cycle.

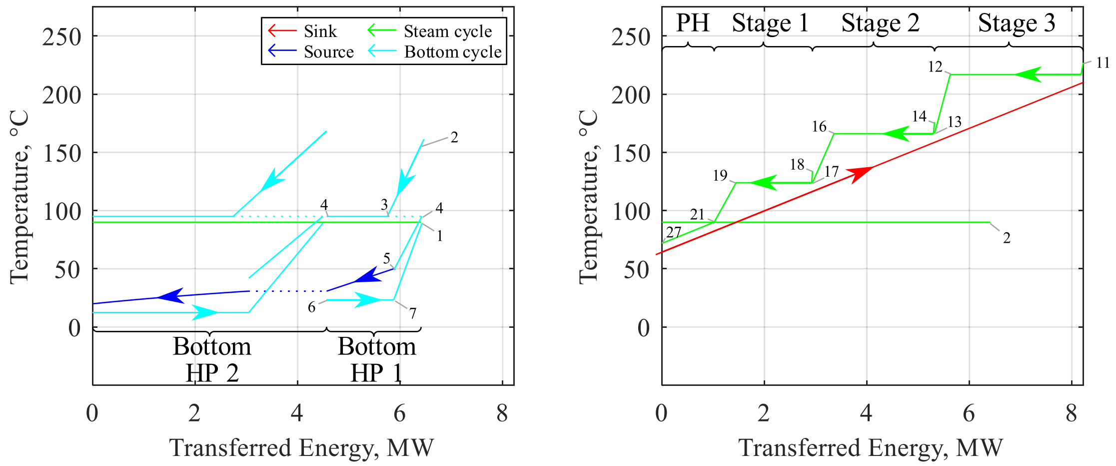

Fig. 5. Temperature-heat-diagram for the bottom cycles using R-600 (left) and the multi-stage top cycle using R–718 (right) for the spray dryer case study. Selected state point numbers are shown for the bottom HP 1 and for the multi-stage cycle.

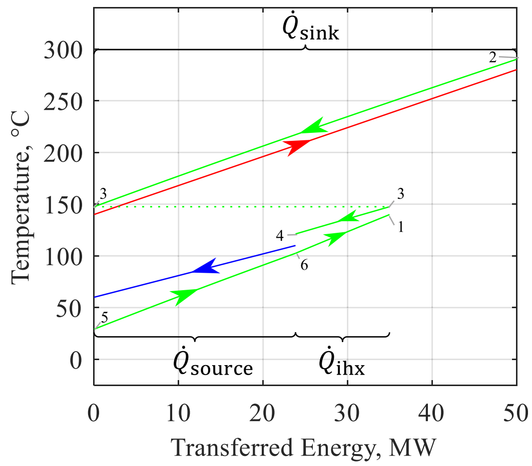

Fig. 6. Temperature-heat-diagram for the reversed Brayton cycle using R-744 for the alumina production case study.

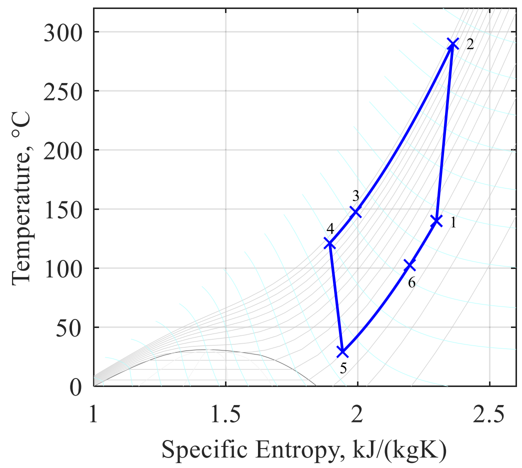

Fig. 7. Temperature-entropy state diagram for the reversed Brayton cycle using R-744 for the alumina production case study.

inlet temperature would allow to design the system with a higher low pressure or respectively, that the heat source could be cooled down further, resulting in an increased heat exchanger area but without compromising the thermodynamic performance.

Fig. 8 shows the temperature-heat-diagram for the case of the spray dryer. The reversed Brayton cycle reached a COP of 1.61 and a Lorenz efficiency of 40 % while operating with a low pressure of 25.2 bar, a high pressure of 72.0 bar and accordingly a pressure ratio of 2.9. The outlet temperature of the compressor was 218 °C.

The temperature-heat-diagram shows a mismatch between the streams in the heat exchangers. This results inevitably in irreversibility and decreased overall performance. In the heat sink, the pinch point occurs at the heat sink outlet, indicating that the thermodynamic performance could be improved by a lower outlet temperature or, respectively, that the heat sink inlet temperature could be higher without having to increase the pressures. On the source side, the inlet temperature of the working fluid lies below 0 °C, while the heat source outlet temperature was around 25 °C. While the characteristic of the condensing moist air is well exploited by the bottom heat pumps of the cascade multi-stage system, there remains some potential for improvements in the case of the reversed Brayton cycle.

An overview of all state points for both cycles and both cases is given in the Appendix.

4.2. Economic analysis of case studies

The suggested systems were furthermore evaluated with respect to their economic performance by determining the investment cost and comparing this to the operating cost. Table 6 shows an overview of the total capital investment TCI for the two systems for both cases. For the

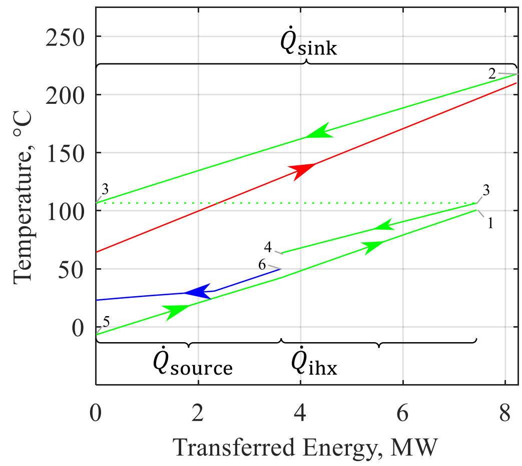

Fig. 8. Temperature-heat-diagram for the reversed Brayton cycle using R-744 for the spray dryer case study.

Table 6
Total capital investment incl. maintenance cost for both cases and both systems incl. subsystems.

Unit	Alumina production		Spray Dryer	
	TCI Mio. €	TCI_{spec} €/kW	TCI Mio. €	TCI_{spec} €/kW
Total cascade multi-stage system	**47.34**	**946**	**16.42**	**1997**
- Top multi-stage cycle (R-718)	22.86		9.30	
- Bottom cycle 1 (R-600)	11.19		2.16	
- Bottom cycle 2 (R-600)	13.29		4.95	
Reversed Brayton system (R-744)	**48.32**	**966**	**15.35**	**1868**

alumina case, the TCI of the cascade multi-stage system was 47 Mio. €, and thereby approximately as expensive as the reversed Brayton system, which had a TCI of 48 Mio. €. For the spray dryer case, the cascade multi-stage system had a TCI of 16 Mio. €, while the reversed Brayton system had a slightly lower TCI of 15 Mio. €. It may furthermore be noted that the specific investment cost were considerably lower for a capacity of 50 MW supplied heat compared to 8.2 MW supplied heat, which corresponds to the expectations with respect to the economy of scale of Aga et al. [37]. While it is expected that the decreased specific investment cost resulted mainly from the upscaling, it may be mentioned, that the specific area of the heat sink heat exchanger was significantly smaller for the alumina case than for the spray dryer case, as the heat transfer coefficient was almost four times larger when heating thermal oil instead of air.

The specific levelized heat generation cost c_h as summarized in Fig. 9 were used to compare the investment cost to the operating cost. The diagram is based on the cost assumptions as introduced in Table 5. The levelized cost was divided into the shares corresponding to fuel consumption and investment. The specific fuel cost for renewable electricity, natural gas, biogas and biomass was specified with a certain range, which is included in the diagram by means of black bars. In order to visualize the impact of a tax on CO_2 emissions, an exemplifying tariff of 50 €/t of CO_2 was assumed and added in the diagram.

The specific levelized cost of heat for the alumina production case varied for both heat pump systems between 45 €/MWh for Denmark and 31 €/MWh for Norway, disregarding any cost for CO_2 emissions. Considering electricity from own renewable electricity facilities, the levelized cost of heat is expected to be between 29 €/MWh and 39 €/MWh for both systems for the alumina case. For the case of the spray dryer, the specific cost of heat were between 9 €/MWh and 12 €/MWh higher, mainly due to higher specific investment cost and a worse COP of the reversed Brayton system.

The investment cost contributed by approximately 10 €/MWh for both systems in case of the alumina production case study, while it reached 20 €/MWh to 22 €/MWh for the spray dryer case study.

An electrical boiler in combination with renewable electricity was considered as an alternative electricity-based heat supply technology. The levelized specific cost of heat was 51 €/MWh with a possible variation between 40 €/MWh and 64 €/MWh. The heat pump systems are accordingly able to compensate the increased investment in terms of levelized cost.

Combustion-based boilers using natural gas, biogas and biomass were considered as further alternatives. The specific investment cost for the gas boilers was minor, while it accounted for approximately 11 €/MWh for the biomass boiler. The levelized cost accumulated 34 €/MWh to 40 €/MWh for natural gas, 73 €/MWh to 85 €/MWh for biogas and 42 €/MWh to 48 €/MWh for biomass, while a potential tax on CO_2 emissions of 50 €/t would yield and additional cost of approximately 10 €/MWh for natural gas.

It may accordingly be summarized that the heat pump systems showed performances which were competitive with natural gas boilers and biomass boilers, when electricity was obtained at low cost. The two heat pump systems were competitive with natural gas boilers without tax on CO_2 emissions, when the electricity was obtained at costs of up to 50 €/MWh in the alumina production case and of up to approximately 35 €/MWh in the spray dryer case. The heat pump systems based on renewable electricity could operate at same levelized cost of heat as a natural gas boiler in the spray dryer case, when a tax of 46 €/t and 35 €/t of CO_2 were assumed for the reversed Brayton system and the multi-stage system, respectively.

Table 7 summarizes the COP, the total capital investment TCI, the net present value NPV, the simple payback times PBT and the internal rate of return IRR for a comparison of the heat pump systems to a combustion-based heat supply. For the alumina production case the

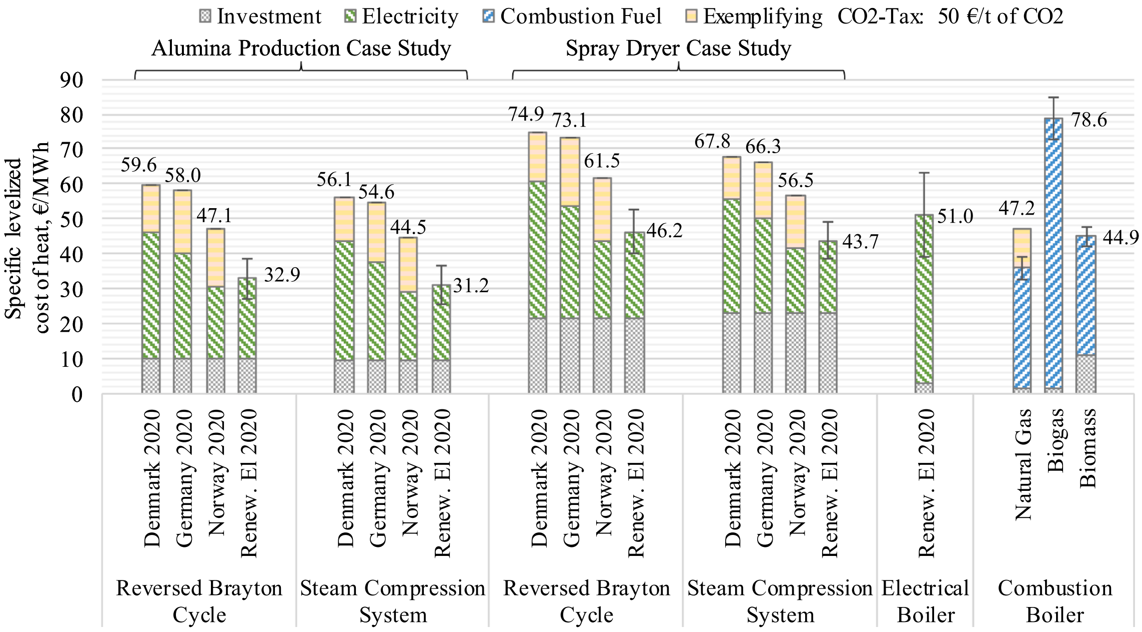

Fig. 9. Specific levelized cost of heat c_h for both case studies including the reversed Brayton cycle, the multi-stage steam compression cycle, an electrical boiler and combustion-based boiler using natural gas, biogas and biomass. The cost scenarios are as defined in Table 5 while the ranges for the cost for electricity from renewables, natural gas, biogas and biomass are indicated by the black bars.

Table 7
Total capital investment TCI, net present value NPV, simple payback time PBT and internal rate of return IRR for both cases and cycles for selected scenarios as defined in Table 5 and assuming specific cost for natural gas of 28.7 €/MWh in Denmark, 33.1 €/MWh in Germany and 27.7 €/MWh in Norway and no taxes for CO_2 emissions. For the comparisons to renewable electricity, the specific cost for natural gas, biogas and biomass were assumed according to the average value as given in Table 5.

	Alumina production		Spray dryer	
	Cascade multi-stage system	Reversed Brayton cycle	Cascade multi-stage system	Reversed Brayton cycle
Coefficient of performance COP, -	1.92	1.72	1.92	1.61
Total capital investment TCI, Mio. €	47.3	48.3	16.4	15.4
Net present value NPV, Mio. €				
Denmark 2020 – NG	−44.8	−64.7	−16.1	−19.5
Germany 2020 – NG	8.05	−8.5	−8.5	−11.1
Norway 2020 – NG	19.6	7.8	−6.8	−8.3
Renewable el 2020 – NG	27.8	14.8	−5.6	−7.4
Renewable el 2020 – BG	241.0	228.1	25.0	23.2
Renewable el 2020 – BM	72.8	59.9	0.8	−1.0
Payback time PBT, years				
Denmark 2020 – NG	–	–	–	–
Germany 2020 – NG	10.7	15.1	25.8	45.4
Norway 2020 – NG	8.8	10.7	21.3	27.2
Renewable el 2020 – NG	7.9	9.5	19.0	24.2
Renewable el 2020 – BG	2.1	2.2	4.9	5.0
Renewable el 2020 – BM	4.9	5.6	11.9	13.3
Internal rate of return IRR, %				
Denmark 2020 – NG	–	–	–	–
Germany 2020 – NG	6.9	2.8	–	–
Norway 2020 – NG	9.5	6.8	–	–
Renewable el 2020 – NG	11.2	8.4	0.5	–
Renewable el 2020 – BG	48.9	45.9	19.7	19.6
Renewable el 2020 – BM	19.8	17.2	5.6	4.2

heat pump systems were outperforming biogas, biomass and natural gas when based on renewable facilities, and were competitive with natural gas when considering Norwegian conditions. For the spray dryer case the heat pump systems became feasible when based on renewable facilities and compared to biogas and biomass, but they were outperformed by natural gas based systems in all scenarios considering no taxes on CO_2 emissions.

The simple payback times PBT shown in Table 7 are below 5 years if the electricity is obtained from own renewable resources and the alternative is biogas in both cases and are below 6 years when compared to biomass in the alumina production case. In the alumina case the reversed Brayton cycle has a PBT of 10 years and the steam compression unit of 8 years when own renewable-based electricity and natural gas consumption from the grid is assumed. The IRR for the reversed Brayton cycle reached 8 % and for the cascade multi-stage system 11 %. These values might be accepted, considering that the investment improves the overall efficiency and constitutes the central utility system, which is associated to corresponding low uncertainties.

The economic results indicated a strong dependency on the specific cost for electricity c_{el} and for the alternative heat supply c_{alt}. In order to analyze this dependency in more detail, a parameter study was conducted. Figs. 10 and 11 show the net present value NPV of the reversed Brayton cycle and the steam compression unit for a variation of the specific cost between 20 €/MWh and 100 €/MWh for the alumina production case study. Additionally, the specific levelized cost of heat for natural gas, biomass and biogas are indicated on the axes. The same information is shown for the steam compression cycle in Fig. 11.

Considering the cheapest cost for the alternative fuel for a natural gas-based combustion process of 33 €/MWh, the NPVs of both technologies become positive for specific electricity costs lower than 40 €/MWh. Presuming that the aim is a fully carbon neutral solution, natural gas is eliminated as a potential alternative and the remaining options considered here are biomass or biogas. The cheapest levelized cost of heat from biomass is around 42 €/MWh. Considering this benchmark, the electrification of the processes using the suggested technologies becomes the preferred choice for electricity generation cost lower than 53 €/MWh. Compared to biogas, the heat pump-based process heat supply constitutes the most favorable solution in all scenarios, incl. "Germany 2020" and "Denmark 2020".

The replacement of a natural gas-based combustion process with specific CO_2 emissions of 0.204 tons/MWh corresponds to an abatement of 90,800 tons of CO_2 per year in the case of the alumina production and to 13,100 tons of CO_2 per year in the case of the spray dryer. Replacing oil or coal based heating utilities results in accordingly higher emission reductions. The impact of increased prices for CO_2 emission certificates on the economic performance was demonstrated in Fig. 9 and may be additionally derived from Figs. 10 and 11 by adding the costs to the alternative fuel costs.

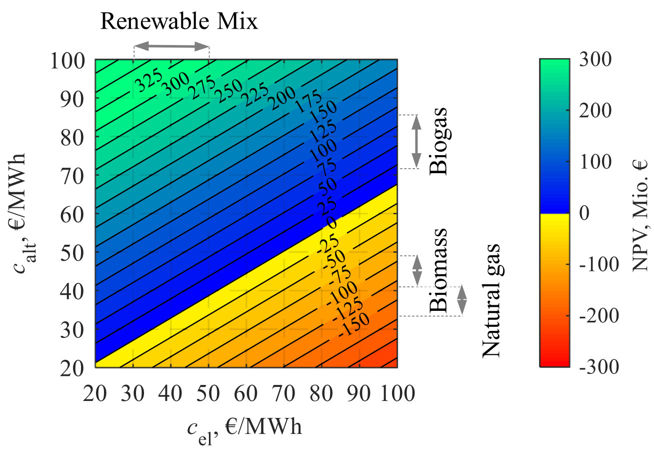

Fig. 10. Net present value NPV for a variation of the specific cost for electricity c_{el} and the alternative heat generation c_{alt} for the reversed Brayton cycle in the alumina production case study with an indication of the specific cost of different energy utilities.

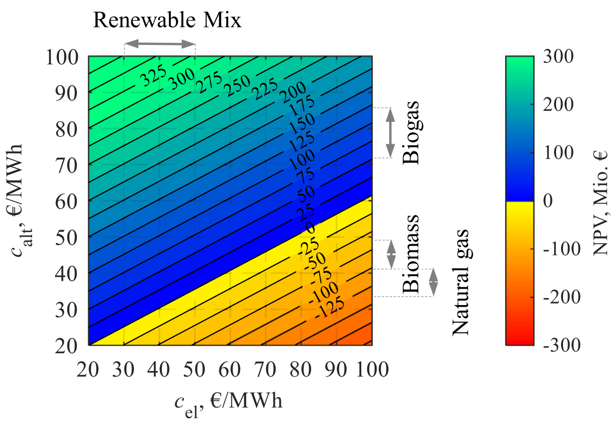

Fig. 11. Net present value NPV for a variation of the specific cost for electricity c_{el} and the alternative heat generation c_{alt} for the steam compression cycle in the alumina production case study with an indication of the specific cost of different energy utilities.

4.3. Identification of additional industrial processes as potential applications

The two case studies demonstrated the thermodynamic, economic and environmental performance of the presented technologies. They indicated that the performance of the heat pumps is strongly dependent on application and thereby subject to site specific parameters. The estimation of the potential does accordingly require inclusion of a detailed energy analysis of the existing process including a reevaluation of design parameters, which were decided considering a fuel-based heat supply.

It can be assumed that similar performances could be obtained for other processes, if adjustments of the production processes are accepted, while heat pump-based solutions are infeasible or unfavorable in other processes. In the following an analysis of the potential of the presented technologies for process heat supply in the range of 100 °C to 400 °C is shown for processes of other industrial sectors.

4.3.1. Chemical and petrochemical industry

The chemical and petrochemical industry in Europe is very diverse, with the German one being the largest. In Germany 25 % of the industrial energy use is associated with this industry sector [9]. The basic chemical industry is characterized by energy intense processes and large operation units, such as the production of ammonia, chlorine, ethylene and polymers. Other chemical industries produce for instance pesticides, paints, soaps, detergents and fibers. Some processes, such as steam crackers, require high temperatures and pressures while others receive the process heat from exothermic reactions, such as reactors. The largest potential for heat pump integration is found in distillation, evaporation, drying and heating processes, which often take place at temperatures between 100 °C and 500 °C [61]. Applications are for example the production of soda ash, where process temperatures of around 160 °C to 230 °C are required in the calcination process, where CO_2 and water are removed. While the main processes for the production of polymers are often exothermic, some process steps require heating. The production of polyamides requires pre-heating and heating in the range of 110 °C to 270 °C [76]. Polysulfones and polycarbonates further require process heat in the magnitude of 6.8 MWh and 3.6 MWh per ton respectively [77]. Process heat is required at temperatures between 120 °C and 300 °C for distillation, reactors, separators and dryers.

Heat pumps were suggested to be integrated for heat supply in hydrogen production processes [78,79] and significant improvements in overall performance were found. The heat pump required for the concept from [78] was required to deliver heat of up to 330 °C while receiving heat at around 265 °C. Almahdi et al. [79] suggested a cascade heat pump operating at even higher temperatures between 290 °C and around 670 °C.

Oil and gas refineries might be another promising application as it comprises energy-intensive processes with heat demands between 250 °C and 400 °C. Nemet et al. [80] performed a heat integration study for an oil refinery, where for one part of a factory a heating demand of more than 4 MW in the temperature range of 350 °C to 400 °C and 3 MW of heat requirement between 250 °C and 350 °C were found. At the same time, cooling of more than 4 MW is required between ambient and 130 °C. The HTHP using the reversed Brayton cycle could be suitable for this application. Oil refineries are however large and complex sites, where total site analyses are required to find the optimal integration strategies.

4.3.2. Ferrous and non-ferrous metal industry

The ferrous and non-ferrous metal industry comprise highly energy-intensive processes [66] and account for 21 % of the energy use in the European industry [9]. Most of the heat is however required at temperatures above 1000 °C and thereby above the techno-economic limitations of heat pumps. The high-temperature processes typically reject excess heat that can be used to cover other processes on site, which limits the potential for heat pump applications. The case study of the bauxite production was a pre-processing step in the aluminum production and locally it is independent of the actual aluminum production. It did however outline the possibility to reduce the overall environmental impact of the metal industry. Further processes in the ferrous and non-ferrous metal industry are in the temperature range between 100 °C and 400 °C. These might not be coverable by excess heat from other processes. Examples of these processes are in the post-processing (e.g., extruding, rolling) of copper and aluminum. In rolling processes, the materials are heated in ovens to temperatures between 350 °C and 510 °C. During the rolling process itself cooling of the rolls and materials take place [81].

4.3.3. Non-metallic mineral industry

The non-metallic mineral industry in Europe has a variety of products, such as cement, bricks, glass and ceramics. It accounted for 12 % of the energy use in the European industry [9]. The main processes take place in dryers and furnaces. While furnaces reach temperatures above 1200 °C, some of the heat is required at lower temperatures. In furnaces for ceramics around 10 % of the process heat demand is required below 500 °C [82]. The drying processes often aim at removing water and preheating the materials. In the production of asphalt the aggregate is dried and heated to temperatures above 200 °C using directly fired rotary dyers [83]. Spray dryers are used in the ceramic industry to remove water from the mud [84]. In the production of bricks and tiles, tunnel dryers are used for the formed materials where drying temperatures above 180 °C are required [85]. The moist air from the dryer is expelled at around 50 °C and latent and sensible heat can be recovered. While some of the available excess heat from the dryers could be used directly in the processes or is supplied from other process steps, e.g., the furnaces, high temperature heat pumps could be used to increase energy efficiency in some cases [85]. The process heat is usually added through direct combustion of natural gas or fuel oil to the processes.

4.3.4. Food and beverage industry

The food industry in Europe accounts for 11 % of the final industrial energy use [49] and includes industries such as meat and dairy processing, breweries and sugar production. The main processes in the food industry consist of pasteurization, sterilization, cooking, evaporation and drying. These processes usually take place below 120 °C. Drying processes however often require temperatures between 150 °C and 250 °C. They are used for many products, such as dairy, fruits, vegetables and beverages. They are also used in other industries in the production of dyestuffs, pigments and pharmaceuticals [86]. An estimated 25,000 spray dryers are commercially in operation worldwide

[86]. In 2016 the EU-28 produced a total of 2.8 million tons of milk powder. Special applications, e.g., found in production of bread, biscuits and cakes, require process temperatures above 170 °C for frying, drying and baking processes. The production of oil and fats has also high process temperatures for the refining and deodorization of the oils. The stripping of the oil, for instance, which removes volatile compounds, requires high temperature (> 200 °C) and pressure process steam, which is injected to the oils. Another example of an energy-intensive drying process is the drying of sugar beets. Superheated steam drying is state-of-the-art and yields promising efficiencies. It may be possible to improve further by using heat pumps, which may be similar to the configurations presented in this paper [87].

5. Discussion

5.1. Process modifications

The example of the alumina production from bauxite indicated that there is a certain freedom for the design of the process with respect to its heat supply. Considering that the heat for preheating and digesting the bauxite is transferred indirectly, the pinch point temperature difference can be chosen as a design parameter. This pinch point temperature difference describes the tradeoff among an increased heat exchanger area requirement at lower temperature differences compared to a decreased efficiency of the steam supply system for higher temperature differences [69–71]. The impact on the efficiency of the steam utility depends on the technology chosen for the heat supply. In conventional combustion-based steam generators, this impact is rather low, while it has a strong impact on the performance of heat pump-based steam generation systems. While pinch point temperature differences of 50 K to 70 K were accepted for conventional systems, values in the order of 10 K and accordingly larger heat exchanger areas are expected from an economic optimization considering heat pump-based steam generation. The results indicated that an additional temperature difference of 40 K to 60 K constitutes a vital impact on the profitability of the heat pumps.

In the case of the spray dryer, it was found that the temperature profiles did not match well. This resulted in a limited thermodynamic performance. The case study was based on a system layout which was already optimized without considering the possibility of a high-temperature heat pump. A simultaneous optimization of the layout considering the possibility of such high temperature heat pumps might result in more favorable conditions.

Based on these examples it can be concluded that a re-evaluation of process parameters that were selected based on combustion-based heat supply technologies are necessary and might be required for the design of an overall profitable solution. Furthermore, it is recommended to ensure that the most cost-effective energy efficiency measures are implemented before the heat pump systems are designed and integrated.

5.2. Flexibility in the design of the two studied concepts

Each process shows specific peculiarities and requires a case specific design of the heat pump solution as well as an analysis of the process parameters. For some processes, specific parameters might however not be adjustable and further process specific peculiarities occur. The spray dryer case involved e.g., moist air with a dew point around 31 °C as heat source. The reversed Brayton cycle had a limited performance due to the temperature profile mismatch in both the heat source and the sink, while the steam compression could be flexibly adjusted to the peculiarities of the process.

5.3. Technical assumptions

The isentropic efficiency for the compressors was assumed as 75 % while an additional efficiency for the drive and the gear of 95 % for each was considered. These efficiencies were conservative estimations and it was expected that these can be achieved or exceeded using state-of-the-art equipment, which might be adjusted to the specific application. The pinch point temperature differences were estimated smaller than for combustion-based systems but in a common range for heat pump systems. Increases in economic performance might be obtainable through a numerical optimization of the temperature differences. This would however require fixed economic boundary conditions and yield case specific results, which was outside the scope of this study. The study assumed furthermore no pressure drops and no heat losses, as this is subject to more detailed engineering. It is however expected that the impact of the pressure drops will be minor for properly designed systems and that the heat losses may be compensated by measures of reasonable economic extent.

The heat exchangers were assumed to be shell and tube heat exchangers, as these were proven technology for these applications and were considered by potential manufacturers [37]. Benefits in economic performance and aspects such as space requirements might however be obtained by selecting another heat exchanger type, such as printed circuit heat exchangers [88].

The limitations that were defined for the compression equipment exceeded the limitations that are typical for conventional heat pump systems [14] but they were in accordance with the values for equipment utilized e.g., in the oil and gas industry, which could potentially be used for these applications as well [37]. The pressure ratios for the R-718 cycle were assumed to be relatively high, which enabled a low number of compression stages but might imply challenges for the compressor design. The allowable pressure ratio and the number of stages might accordingly be optimized in a more detailed economic analysis.

One of the aspects that contributed to the choice of the studied systems was the state of the art of potential components. By the time of the publication, no publicly available documentation of demonstrations in full or lab scale could be found for any of the presented systems at the considered operating conditions. Aga et al. [37] do however emphasize, that the system is based on components that are commercially available and tested for the considered operating conditions and scales, while the reversed Brayton cycle is a known system as used in e.g., cryogenics. The multi-stage compression system used steam, which is widely used and a proven technology as utility system. Special requirements occur for the compressor, due to the high compressor outlet temperatures. Suitable equipment can however be found in oil and gas industries, while the operating requirements might be simplified by introducing more compression stages. It may accordingly be concluded that the Technology Readiness Level of both technologies in the suggested configurations and for the given applications is relatively low, while the conditions are promising to enable a fast development and up-scaling.

5.4. Uncertainties in the cost estimations

Some heat exchanger equipment was larger than the range for which the cost functions were developed and validated. It is expected that such heat exchanger equipment can be manufactured. The form of the cost functions is based on experiences from scaling equipment in general and it was therefore concluded that the estimates are still acceptable for equipment that is larger than the validated range. The estimates are however subject to increased uncertainties that would have to be analyzed during more detailed engineering.

It was furthermore indicated, that process modifications might potentially be required to enable optimal overall performances. The cost associated with such modifications is however dependent on the case-specific boundary conditions and to be considered accordingly in more detailed case studies.

The cost for operation and maintenance of the heat pump systems is expected to be higher than for boilers. A reliable evaluation of the operation and maintenance cost would however require a detailed analysis of both the complete existing and the complete heat pump-based system and is therefore as well recommended for further, more detailed studies.

5.5. Cost of biomass and natural gas

The comparisons used the combustion of biomass and natural gas as benchmark scenarios. These resources are however limited and their prices are therefore affected by availability. Considering that coal and oil are eliminated as acceptable alternatives for combustion processes, the demand for the remaining alternatives will increase. The high-temperature processes will be prioritized, resulting in an increasing scarcity of these resources and thereby in increasing prices. The effective heat generation price for natural gas-based combustions is furthermore subject to political measures, such as the EU Emission Trading System, which might imply additional cost associated to emitting CO_2. These mechanisms are expected to result in the market becoming more beneficial for electricity-based solutions, but they are difficult to quantify and therefore they were omitted from the current study.

In the scenarios in which the heat pump-based solutions had the lowest NPVs, namely "Germany 2020" and "Denmark 2020", the taxes for electricity consumption were higher than for natural gas. Considering the increasing awareness of the climate impact of fossil fuels and the increasing share of renewables in the electricity generation, it may be expected to change.

5.6. Acceptance of long payback periods

The presented technologies constitute a large investment, which typically requires low uncertainties to gain acceptance. The payback time was introduced as a measure to evaluate the uncertainties associated with the investment, as it describes the time span in which the investment is amortized. The accepted payback times depend on the uncertainties as well as on further factors, such as an increased plant competitiveness which might result from the investment.

Henrickson [89] studied different energy efficiency measures under consideration of the current economic situation, meaning developments of costs of fuels and bauxite, as well as of the product. He outlined the large contribution of energy to the operational expenditures and indicated that this will become even more dominating in the future. Based on this, Henrickson [89] concludes that longer payback times are accepted in the context of an ongoing modernization focusing on energy efficiency improvements, as such measures are resulting in an improved long term competitiveness.

The development of the energy costs constitutes one of the most uncertain assumptions in the economic evaluation. A general trend of decreasing cost for electricity generation from renewables and increasing cost for the combustion of fossil fuels, due to its environmental impact and decreasing availability, is expected [51], but not guaranteed. The exact development of costs is subject to political measures and market developments.

5.7. Acquisition and operation of own utility production

Philibert [11] outlined the possibility to acquire own renewable electricity utilities, which results not only in low but also stable electricity prices. The levelized cost of electricity from renewables was found to typically lie below the market prices. Owning both the electricity generation as well as the electricity consumption might furthermore enable the possibility to more effectively control the electricity consumption in accordance with its availability. The considered costs were assumed to be effective levelized costs, excluding cost for operation and control of the electricity system. The obtainable levelized cost of electricity depends furthermore on the approach to handle the variations in electricity supply. The variations might be compensated by local electricity storage or by the electricity grid, which in turn might be associated to a certain cost. It is also possible to choose a larger heat pump capacity in combination with thermal storages to obtain the possibility to vary the electricity consumption according to variable electricity input. The optimal combination of these measures is determined by case specific boundary conditions and subject to more detailed engineering.

Many industrial sites, especially large ones, generate their own heat in boilers, which are often coupled with gas turbines to produce electricity. The use of gas turbines in combination with a combined heat production is often seen as an energy efficiency measure for many industries [90,91]. They become however obsolete if no fuels are used. In 2016, industries in Germany produced 35.3 TWh of electricity, of which 86 % were fossil fuel-based [92]. This represents an industry self-supply with electricity of more than 15 %.

6. Conclusion

This work analyzed the techno-economic feasibility of two heat pump systems for the supply of process heat at high temperatures in large-scale applications. The two identified solutions were a reversed Brayton cycle using R-744 (CO_2) as working fluid and a cascade multi-stage compression cycle using R-718 (water) as working fluid in the high temperature section. It was found that equipment suitable for the operating conditions is available in oil and gas industries rather than in heat pump industries.

The analysis of the case studies indicated the possibility to economically supply process heat by electrically driven heat pumps at temperatures of up to 280 °C, while higher temperatures might be reached depending on the availability of suitable heat sources. The economic potential was highest for low electricity prices and it was emphasized that the acquisition and operation of own renewable electricity utilities becomes promising, especially for energy-intensive industries.

The comparison of the reversed Brayton cycle and the multi-stage steam compression cycle revealed competitive performances for both cycles in the considered applications, while the preferred choice is determined by the specific application. The reversed Brayton cycle is a simpler construction and is more promising in applications with large temperature glides. The reversed Brayton cycle had in both case studies a lower thermodynamic performance. Due to its simpler construction and lower investment costs, it had better economic performance in one case study. The cascade multi-stage cycle showed a higher flexibility with respect to the integration into given boundary conditions and had a higher thermodynamic performance. The increased flexibility is related to a more complex construction and accordingly higher investment cost, which might be compensated by the higher thermodynamic performance.

It was demonstrated that a heat pump-based process heat supply is technically feasible at temperatures of up to 300 °C to 400 °C. This enables supply of heat at higher temperatures and coverage of even more applications by electricity-based heat supply. This improves the overall energy efficiency of the plants and reduces the environmental impact from fossil fuel combustion. A large potential for implementing these technologies across many manufacturing industries was expected and possible other applications were pointed out.

The examples have furthermore highlighted, that the transition to heat pump-based process heat supply with an overall optimal energetic and economic performance requires a simultaneous and multi-disciplinary development including possible adjustments in the process, the design of the heat pump and the design of the components.

Declaration of Competing Interest

None.

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Appendix

This section summarizes the state points of the numerical simulations as well as the component data for the economic evaluation.

Cascade multi-stage steam compression cycle (R-718)

Table A.1 summarizes the state points of the system as modelled for the alumina production case study. It includes the state points for both the top cycle and the two bottom heat pump cycles. The source and sink stream were assumed to be of constant heat capacity and not further specified. They are therefore omitted from the list. The source was cooled from 110 °C to 60 °C while the sink stream was heated from 140 °C to 280 °C. In the alumina production case study, no direct heating with liquid from the evaporator was required and the streams 26 and 27 were accordingly obsolete.

Table A.2 shows the state points of the cascade multi-stage system for the spray dryer case study including the bottom heat pump cycles and the heat source and sink streams.

Table A1
Thermodynamic modelling results of cascade multi-stage R-718 system for the alumina production case study.

State point	Mass flow rate kg/s	Pressure bar	Temp. °C	Spec. Enthalpy kJ/kg
Top cycle (R-718)				
1	–	2.3	125.0	525.1
2	16.9	2.3	125.0	2713.1
3	18.0	2.3	135.0	2734.8
4	16.9	7.4	302.2	3063.0
5	18.9	7.4	177.4	2790.1
6	16.1	7.4	177.4	2790.1
7	16.1	2.4	354.9	3140.8
8	18.3	2.4	231.3	2833.0
9	10.6	2.4	231.3	2833.0
10	10.6	6.8	397.3	3156.8
11	12.1	6.8	293.4	2823.7
12	12.1	6.8	283.4	1254.6
13	12.1	6.8	222.0	954.0
14	7.7	23.8	231.3	2833.0
15	7.7	23.8	221.3	949.6
16	19.8	23.8	221.3	952.3
17	19.8	23.8	167.4	708.5
18	2.8	7.4	177.4	2790.1
19	2.8	7.4	167.4	707.6
20	22.6	7.4	167.4	708.4
21	22.6	7.4	145.0	610.8
22	22.6	2.3	125.0	610.8
23	2.0	7.4	125.1	525.7
24	2.2	23.8	125.2	527.6
25	1.5	67.5	125.8	532.8
Bottom HP 1 (R-600)				
1	53.65	9.6	124.9	800.4
2	53.65	26.3	169.0	866.0
3	53.65	26.3	130.0	747.1
4	53.65	26.3	130.0	562.6
5	53.65	26.3	97.8	454.9
6	53.65	9.6	77.5	454.9
7	53.65	9.6	77.5	693.0
Bottom HP 2 (R-600)				
1	51.35	5.3	124.9	811.1
2	51.35	26.3	190.2	924.3
3	51.35	26.3	130.0	747.1
4	51.35	26.3	130.0	562.5
5	51.35	26.3	82.5	410.2
6	51.35	5.3	52.5	410.2
7	51.35	5.3	52.5	659.0

Table A2
Thermodynamic modelling results of cascade multi-stage R-718 system for the spray dryer case study.

State point	Mass flow rate kg/s	Pressure bar	Temp. °C	Spec. Enthalpy kJ/kg
Top cycle (R-718)				
1	–	0.7	90.0	377.0
2	2.36	0.7	90.0	2659.5
3	2.52	0.7	100.0	2679.8
4	2.36	2.3	257.1	2984.6
5	2.61	2.3	133.9	2733.2
6	1.94	2.3	133.9	2733.2
7	1.94	7.2	300.9	3060.8
8	2.16	7.2	176.0	2788.6
9	1.22	7.2	176.0	2788.6
10	1.22	21.8	344.0	3120.3
11	1.36	21.8	226.8	2830.9
12	1.36	21.8	216.8	928.6
13	1.36	21.8	166.4	704.3
14	0.94	7.2	176.0	2788.6
15	0.94	7.2	166.0	701.6
16	2.30	7.2	166.0	703.2
17	2.30	7.2	123.9	520.8
18	0.67	2.3	133.9	2733.2
19	0.67	2.3	123.9	520.5
20	2.98	2.3	123.9	520.7
21	2.98	2.3	90.0	377.2
22	2.98	0.7	90.0	377.2
23	0.25	2.3	90.0	377.2
24	0.22	7.2	90.1	377.8
25	0.14	21.8	90.2	379.5
26	13.34	0.7	90.0	377.2
27	13.34	0.7	71.8	300.6
Bottom HP 1 (R-600)				
1	4.39	2.3	89.0	742.7
2	4.39	13.7	156.1	864.3
3	4.39	13.7	95.0	714.6
4	4.39	13.7	95.0	446.2
5	4.39	13.7	48.8	319.4
6	4.39	2.3	23.3	319.4
7	4.39	2.3	23.3	617.7
Bottom HP 2 (R-600)				
1	10.1	1.6	89.0	744.6
2	10.1	13.7	168.3	894.3
3	10.1	13.7	95.0	714.6
4	10.1	13.7	95.0	446.1
5	10.1	13.7	42.0	302.0
6	10.1	1.6	12.4	302.0
7	10.1	1.6	12.4	602.2
Heat sink stream (Moist air, humidity at inlet: 6.43 g/kg)				
Si1	54.9	1.0	64.3	81.5
Si2	54.9	1.0	82.5	100.0
Si3	54.9	1.0	90.1	107.8
Si4	54.9	1.0	116.7	135.0
Si5	54.9	1.0	124.1	142.6
Si6	54.9	1.0	158.9	178.4
Si7	54.9	1.0	164.3	183.9
Si8	54.9	1.0	210.0	231.2
Heat source stream (Moist air, humidity at inlet: 28.88 g/kg)				
So1	64.3	1.0	50.0	125.2
So2	64.3	1.0	30.8	104.8
So3	64.3	1.0	19.9	57.7

Reversed Brayton cycle (R-744)

Table A.3 shows the state points for the reversed Brayton cycle for the alumina production case study. The source and sink stream were assumed to be of constant heat capacity and not further specified. They were therefore omitted from the table. The source was cooled from 110 °C to 60 °C while the sink stream was heated from 140 °C to 280 °C.

Table A.4 shows the state points of the reversed Brayton cycle for the spray dryer case including the heat source and sink streams.

Table A3
Thermodynamic modelling results of the reversed Brayton cycle for the alumina production case study.

State point	Mass flow rate kg/s	Pressure bar	Temp. °C	Spec. Enthalpy kJ/kg
Reversed Brayton cycle (R-744)				
1	278.7	40.7	139.9	83.6
2	278.7	140.0	290.0	220.9
3	278.7	140.0	147.5	41.5
4	278.7	140.0	121.2	1.6
5	278.7	40.7	29.1	−41.8
6	278.7	40.7	102.5	43.7

Table A4
Thermodynamic modelling results of the reversed Brayton cycle for the spray dryer case study.

State point	Mass flow rate kg/s	Pressure bar	Temp. °C	Spec. Enthalpy kJ/kg
Reversed Brayton cycle (R-744)				
1	64.3	25.2	100.6	51.6
2	64.3	72.0	217.5	155.4
3	64.3	72.0	106.6	27.5
4	64.3	72.0	63.6	−31.9
5	64.3	25.2	−6.8	−64.2
6	64.3	25.2	42.3	−7.9
Heat sink stream (Moist air, humidity at inlet: 6.43 g/kg)				
Si1	54.9	1.0	64.3	81.5
Si2	54.9	1.0	210.0	231.2
Heat source stream (Moist air, humidity at inlet: 28.88 g/kg)				
So1	64.3	1.0	50.0	125.2
So2	64.3	1.0	23.0	68.9

References

[1] Kost C, Shammugam S, Jülch V, Nguyen H-T, Schlegl T, Henning H-M, et al. Levelized Cost of Electricity - Renewable Energy Technologies 2018. https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html (accessed January 14, 2019).

[2] Schlesinger M, Hofer P, Kemmler A, Kirchner A, Koziel S, Ley A, et al. Development of energy markets - Energy reference forecast [In German: Entwicklung der Energiemärkte – Energiereferenzprognose]. Prognos 2014:Projekt Nr. 57/12. https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/entwicklung-der-energiemaerkte-energiereferenzprognose-endbericht.pdf?__blob=publicationFile&v=7 (accessed January 15, 2019).

[3] European Commission. A Roadmap for moving to a competitive low carbon economy in 2050 2011. https://ec.europa.eu/clima/policies/strategies/2050_en#tab-0-1 (accessed January 15, 2019).

[4] Danish Ministry of Energy Utilities and Climate. Energistrategi 2050 - fra kul, olie og gas til grøn energi 2011:65. https://www.regeringen.dk/tidligere-publikationer/energistrategi-2050-fra-kul-olie-og-gas-til-groen-energi/ (accessed January 15, 2019).

[5] Sustainable Development Solutions Network (SDSN), Institute for Sustainable Development and International Relations (IDDRI). Deep Decarbonization Pathways Project – Pathways to deep decarbonization 2015:1–58. http://deepdecarbonization.org/wp-content/uploads/2016/03/DDPP_2015_REPORT.pdf%0Apapers2://publication/uuid/E7622E05-580D-4FEC-9AB7-DFE70AA5D572.

[6] Bataille C, Åhman M, Neuhoff K, Nilsson LJ, Fischedick M, Lechtenböhmer S, et al. A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris agreement. J Clean Prod 2018;187:960–73. https://doi.org/10.1016/j.jclepro.2018.03.107.

[7] UNFCCC Paris Agreement. Conf Parties Its Twenty-First. Sess 2015;32.

[8] McMillan C, Boardman R, Mckellar M, Sabharwall P, Ruth M, Bragg-sitton S, et al. Generation and use of thermal energy in the U. S. Industrial sector and opportunities to reduce its carbon emissions. NREL/TP-6A50-66763 2016.

[9] Eurostat. Energy statistics – supply, transformation and consumption, 2017.

[10] Wolf S, Blesl M. Model-based quantification of the contribution of industrial heat pumps to the European climate change mitigation strategy. ECEEE Ind Summer Study Proc 2016:477–87.

[11] Philibert C. Renewable Energy for Industry – From green energy to green materials and fuels. Int Energy Agency 2017:72 (accessed January 15, 2019).

[12] Esser A, Sensfuss F. Final report - Evaluation of primary energy factor calculation options for electricity 2016:121. https://ec.europa.eu/energy/sites/ener/files/documents/final_report_pef_eed.pdf (accessed January 15, 2019).

[13] Elmegaard B, Zühlsdorf B, Reinholdt L, Bantle M, editors. International Workshop on High Temperature Heat Pumps. B Present Int Work High Temp Heat Pumps 2017:176. http://orbit.dtu.dk/en/publications/book-of-presentations-of-the-international-workshop-on-high-temperature-heat-pumps (0351887a-6b82-4b3d-aae5-19181db64891).html (accessed January 15, 2019).

[14] Arpagaus C, Bless F, Uhlmann M, Schiffmann J, Bertsch SS. High temperature heat pumps: market overview, state of the art, research status, refrigerants, and application potentials. Energy 2018:152. https://doi.org/10.1016/j.energy.2018.03.166.

[15] Wolf S, Fahl U, Blesl M, Voss A, Jakobs R. Forschungsbericht – Analyse des Potenzials von Industriewärmepumpen in Deutschland 2014:150. http://www.ier.uni-stuttgart.de/publikationen/veroeffentlichungen/forschungsberichte/downloads/141216_Abschlussbericht_FKZ_0327514A.pdf (accessed January 15, 2019).

[16] Pehnt M, Bödeker J, Arens M, Jochem E, Idrissova F. Die Nutzung industrieller Abwärme – technisch-wirtschaftliche Potentiale und energiepolitische Umsetzung 2010:49. https://www.ifeu.de/wp-content/uploads/Nutzung_industrieller_Abwaerme.pdf (accessed January 15, 2019).

[17] Thekdi A, Nimbalkar SU. Industrial waste heat recovery: potential applications. Avail Technol Crosscutting R&D Opport 2014. https://doi.org/10.2172/1185778.

[18] Kang DH, Na S-I, Kim MS. Recent researches on steam generation heat pump system. Int J Air-Condition Refrig 2017. https://doi.org/10.1142/S2010132517300051.

[19] Bless F, Arpagaus C, Bertsch SS, Schiffmann J. Theoretical analysis of steam generation methods – energy, CO2emission, and cost analysis. Energy 2017;129:114–21. https://doi.org/10.1016/j.energy.2017.04.088.

[20] Kaida T, Sakuraba I, Hashimoto K, Hasegawa H. Experimental performance evaluation of heat pump-based steam supply system. IOP Conf Ser: Mater Sci Eng 2015;90:012076. https://doi.org/10.1088/1757-899X/90/1/012076.

[21] Lee G, Lee B, Cho J, Ra H-S, Baik Y, Shin H-K, et al. Development of steam

generation heat pump through refrigerant replacement approach. Rotterdam: 12th IEA Heat Pump Conf.; 2017. p. 1–10. Paper ID: P.3.3.2.
[22] Meroni A, Zühlsdorf B, Elmegaard B, Haglind F. Design of centrifugal compressors for heat pump systems. Appl Energy 2018;232:139–56. https://doi.org/10.1016/j.apenergy.2018.09.210.
[23] Bühler Fabian, Zühlsdorf Benjamin, Nguyen Tuong-Van, Elmegaard Brian. A comparative assessment of electrification strategies for industrial sites: Case of milk powder production. Appl Energy 2019;250:1383–401. https://doi.org/10.1016/j.apenergy.2019.05.071.
[24] Madsbøll H, Weel M, Kolstrup A. Development of a water vapor compressor for high temperature heat pump applications. Yokohama, Japan: Proc. Int. Congr. Refrig.; 2015. p. 845.
[25] Bantle M, Tolstorebrov I, Eikevik TM. Possibility for mechanical vapor re-compressrion for steam based drying processes. Proc. 1st Nord. Balt. Dry. Conf. 2015.
[26] Bantle M. Turbo-compressors : Prototype tests of mechanical vapour re-compression for steam driers. Rotterdam: Proc. 12th IEA Heat Pump Conf.; 2017. Paper ID: O.3.5.4.
[27] Bantle M, Schlemminger C, Tolstorebrov I, Ahrens M, Evenmo K. Performance evaluation of two stage mechanical vapour recompression with turbo-compressors. Proc. 13th IIR Gustav Lorentzen Conf. Nat. Refrig.; 2018. p. 1157. 10.18462/iir.gl.2018.1157.
[28] Zühlsdorf B, Schlemminger C, Bantle M, Evenmo K, Elmegaard B. Design Recommendations for R718 Heat Pumps in High Temperature Applications. Valencia: Proc. 13th IIR Gustav Lorentzen Conf. Nat. Refrig.; 2018. 10.18462/iir.gl.2018.1367.
[29] Chamoun M, Rulliere R, Haberschill P, Peureux J-L. Experimental and numerical investigations of a new high temperature heat pump for industrial heat recovery using water as refrigerant. Int J Refrig 2014;44:177–88. https://doi.org/10.1016/j.ijrefrig.2014.04.019.
[30] Chamoun M, Rulliere R, Haberschill P, Peureux J-L. Experimental investigation of a new high temperature heat pump using water as refrigerant for industrial heat recovery. Purdue: Proc. Int. Refrig. Air Cond. Conf.; 2012. Paper ID 2108.
[31] De Larminat P, Arnou D, Le Sausse P, Clunet F, Peureux J-L. A High Temperature Heat Pump Using Water Vapor as Working Fluid. Hangzhou, China: Proc. 11th IIR Gustav Lorentzen Conf.; 2014. Paper No.: GL-55.
[32] Šarevski MN, Šarevski VN. Thermal characteristics of high-temperature R718 heat pumps with turbo compressor thermal vapor recompression. Appl Therm Eng 2017;117:355–65. https://doi.org/10.1016/j.applthermaleng.2017.02.035.
[33] Šarevski MN, Šarevski VN. Characteristics of water vapor turbocompressors applied in refrigeration and heat pump systems. Int J Refrig 2012;35:1484–96. https://doi.org/10.1016/j.ijrefrig.2012.03.014.
[34] Zühlsdorf B, Bühler F, Mancini R, Cignitti S, Elmegaard B. High Temperature Heat Pump Integration using Zeotropic Working Fluids for Spray Drying Facilities. Rotterdam: 12th IEA Heat Pump Conf.; 2017. p. 1–11.
[35] Angelino G, Invernizzi C. Prospects for real-gas reversed Brayton cycle heat pumps. Int J Refrig 1995;18:272–80. https://doi.org/10.1016/0140-7007(95)00005-V.
[36] Fu C, Gundersen T. A novel sensible heat pump scheme for industrial heat recovery. Ind Eng Chem Res 2016;55:967–77. https://doi.org/10.1021/acs.iecr.5b02417.
[37] Aga V, Conte E, Carroni R, Burcker B, Ramond M. Supercritical CO2-Based Heat Pump Cycle for Electrical Energy Storage for Utility Scale Dispatchable Renewable Energy Power Plants. San Antonio Texas: 5th Int. Supercrit. CO2 Power Cycles Symp; 2016.
[38] Malpiece D, Montressor P, Aga VK, Nikulshyna V. Electrical energy storage and discharge system. EP 2 942 492 Al 2015.
[39] Aga V, Conte E. Electrical energy storage and discharge system. EP 3 054 155 B1 2017.
[40] Bamigbetan O, Eikevik TM, Nekså P, Bantle M, Schlemminger C. Theoretical analysis of suitable fluids for high temperature heat pumps up to 125 °C heat delivery. Int J Refrig 2018;92:185–95. https://doi.org/10.1016/j.ijrefrig.2018.05.017.
[41] Zühlsdorf B, Jensen JK, Elmegaard B. Heat pump working fluid selection – economic and thermodynamic comparison of criteria and boundary conditions. Int J Refrig 2019;98:500–13. https://doi.org/10.1016/j.ijrefrig.2018.11.034.
[42] Zühlsdorf B, Jensen JK, Elmegaard B. Numerical models for the design and analysis of heat pumps with zeotropic mixtures, Rev01 2018. doi: https://doi.org/10.11583/DTU.6825443.
[43] Lorenz H. Beiträge zur Beurteilung von Kühlmaschinen. Zeitschrift Des VDI 1894;38:62–8.
[44] Bejan A, Tsatsaronis G, Moran M. Thermal Design and Optimization 1996. https://doi.org/10.1016/S0140-7007(97)87632-3.
[45] VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen. VDI Heat Atlas. Berlin, Heidelberg: Springer Berlin Heidelberg; 2010.
[46] Turton R, Bailie RC, Whiting WB, Shaeiwitz JA, Bhattacharyya D. Analysis Synthesis, and Design of Chemical Processes. Fourth Pearson Education, Inc.; 2012.
[47] Ulrich GD, Vasudevan PT. Chemical Engineering Process Design and Economics: A Practical Guide. Durham, New Hampshire: Process Publishing Company; 2004.
[48] Towler G, Sinnott R. Chemical Engineering Design - Principles, Practice and Economics of Plant and Process Design. 2nd ed. Elsevier Ltd.; 2012. 10.1016/C2009-0-61216-2.
[49] Eurostat. Energy statistics - supply, transformation and consumption 2017. https://ec.europa.eu/eurostat/web/energy/data/database?p_p_id=NavTreeportletprod_WAR_NavTreeportletprod_INSTANCE_QAMy7Pe6HwI1&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&p_p_col_id=column-2&p_p_col_count=1 (accessed January 14, 2019).
[50] Danish Energy Agency. Finding your cheapest way to a low carbon future: The Danish Levelized Cost of Energy Calculator 2017. https://ens.dk/en/our-responsibilities/global-cooperation/levelized-cost-energy-calculator (accessed January 15, 2019).
[51] Kost C, Shammugam S, Jülch V, Nguyen H-T, Schlegl T, Henning H-M, et al. Level Cost Electricity – Renew Energy Technol 2018.
[52] Statnett. Long Term Market Analysis, the Nordic Region and Europe 2016. https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/planer-og-analyser/long-term-market-analysis-the-nordic-region-and-europe-2016-2040.pdf (accessed January 15, 2019).
[53] The Norwegian Tax Administration. Electrical power tax - The Norwegian Tax Administration 2018. https://www.skatteetaten.no/en/business-and-organisation/vat-and-duties/excise-duties/about-the-excise-duties/electrical-power-tax/ (accessed January 15, 2019).
[54] PwC (Price Waterhouse Coopers). Overview for the accounting and reimburesment of taxes [In Danish: Samlet overblik over afregning og godtgørelse af afgifter] 2018. https://www.pwc.dk/da/publikationer/2019/01/afgiftsvejledning.html.
[55] Danish Energy Agency. Baseline projection 2018 [Basisfremskrivning 2018] 2018. https://ens.dk/sites/ens.dk/files/Analyser/basisfremskrivning_2018.pdf (accessed January 15, 2019).
[56] Danish Energy Agency. Technology Data for Individual Heating Plants 2016. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-individual-heating-plants (accessed January 15, 2019).
[57] Danish Energy Agency. Biogas in Denmark- status, barriers and perspectives [In Danish: Biogas i Danmark-status, barrierer og perspektiver] 2014. https://ens.dk/sites/ens.dk/files/Bioenergi/biogas_i_danmark_-_analyse_2014-final.pdf (accessed January 15, 2019).
[58] Danish Energy Agency. Socioeconomic calculation basis for energy prices and emissions [In Danish: Samfundsøkonomiske beregningsforudsætninger for energipriser og emissioner] 2017:25. https://ens.dk/sites/ens.dk/files/Analyser/samfundsoekonomiske_beregningsforudsaetninger_2017.pdf (accessed January 15, 2019).
[59] Gomez DR, Watterson JD, Americano BB, Ha C, Marland G, Matsika E, et al. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2: Energy. Chapter 2: Stationary Combustion. 2007.
[60] Naegler T, Simon S, Klein M, Gils HC. Quantification of the European industrial heat demand by branch and temperature level. Int J Energy Res 2015;39:2019–30. https://doi.org/10.1002/er.3436.
[61] Rehfeldt M, Fleiter T, Toro F. A bottom-up estimation of the heating and cooling demand in European industry. Energy Effic 2018;11:1057–82. https://doi.org/10.1007/s12053-017-9571-y.
[62] McKenna RC, Norman JB. Spatial modelling of industrial heat loads and recovery potentials in the UK. Energy Policy 2010;38:5878–91. https://doi.org/10.1016/j.enpol.2010.05.042.
[63] Hammond GP, Norman JB. Heat recovery opportunities in UK industry. Appl Energy 2014;116:387–97. https://doi.org/10.1016/j.apenergy.2013.11.008.
[64] Fleiter T, Fehrenbach D, Worrell E, Eichhammer W. Energy efficiency in the German pulp and paper industry – a model-based assessment of saving potentials. Energy 2012;40:84–99. https://doi.org/10.1016/j.energy.2012.02.025.
[65] Bengtsson C, Nordman R, Berntsson T. Utilization of excess heat in the pulp and paper industry – a case study of technical and economic opportunities. Appl Therm Eng 2002;22:1069–81. https://doi.org/10.1016/S1359-4311(02)00017-0.
[66] Norgate TE, Jahanshahi S, Rankin WJ. Assessing the environmental impact of metal production processes. J Clean Prod 2007;15:838–48. https://doi.org/10.1016/j.jclepro.2006.06.018.
[67] Donaldson DJPE. Perspective of Bayer Process Energy. Light Met 2013:711–5.
[68] Metson J. Production of Alumina Fundam. Alum. Metall. Prod. Process. Appl., Woodhead Publishing Limited; 2011. p. 23–48. 10.1016/B978-1-84569-654-2.50002-X.
[69] Wischnewski R, Maues Jr CDA, Moraes ELS, Monteiro AB. Alunorte global energy efficiency. Light Met 2011:179–84.
[70] Kelly R, Edwards M, Deboer D, Mcintosh P. New technology for digestion of bauxites. Light Met 2006:371–6.
[71] Songqing G, Zhonglin Y. Preheaters and digesters in the bayer digestion process. Light Met 2004:356–61.
[72] Scarsella AA, Noack S, Gasafi E, Klett C, Koschnick A. Energy in alumina refining: setting new limits. Light Met 2015;2015:131–6. https://doi.org/10.1002/9781119093435.ch24.
[73] Ilievski D, Hay P, Mills G, Bauer G, Bayer Ünal A. Calcination waste heat recovery. Proc. 8th Int. Alumina Qual. Work; 2008. p. 125–9.
[74] Singh RP, Heldman DR. Introduction to Food Engineering. 5th ed. Elsevier Inc.; 2014.
[75] Bühler F, Nguyen T-V, Jensen JK, Holm FM, Elmegaard B. Energy, exergy and advanced exergy analysis of a milk processing factory. Energy 2018;162:576–92. https://doi.org/10.1016/j.energy.2018.08.029.
[76] European Commission. Reference document on best available techniques in the production of polymers 2007:314. http://eippcb.jrc.ec.europa.eu/reference/BREF/pol_bref_0807.pdf (accessed January 15, 2019).
[77] Fleiter T, Schlomann B, Eichhammer W. Energy use and CO2-emissions of industrial process technologies - saving potentials, barriers and instruments [In German: Energieverbrauch und CO2 -Emissionen industrieller Prozesstechnologien – Einsparpotenziale, Hemmnisse und Instrumente]. Stuttgart: Fraunhofer Verlag; 2013.
[78] Dumont Y, Aujollet P, Ferrasse JH. Use of a heat pump to supply energy to the iodine-sulphur thermochemical cycle for hydrogen production. Int J Chem React Eng 2010:8.
[79] Almahdi M, Dincer I, Rosen MA. A new integrated heat pump option for heat upgrading in Cu-Cl cycle for hydrogen production. Comput Chem Eng 2017;106:122–32. https://doi.org/10.1016/j.compchemeng.2017.05.009.
[80] Nemet A, Klemeš JJ, Varbanov PS, Mantelli V. Heat Integration retrofit analysis an oil refinery case study by Retrofit Tracing Grid Diagram. Front Chem Sci Eng 2015;9:163–82. https://doi.org/10.1007/s11705-015-1520-8.
[81] Norsk Hydro ASA. Rolling processes [In German: Walzprozesse] 2016. https://www.hydro.com/de/hydro-in-deutschland/Walzprodukte/Walzprozesse/ (accessed January 15, 2019).
[82] Utlu Z, Hepbaşlı A. Exergoeconomic analysis of energy utilization of drying process in a ceramic production. Appl Therm Eng 2014;70:748–62. https://doi.org/10.

1016/j.applthermaleng.2014.05.070.
[83] Rubio MC, Martínez G, Baena L, Moreno F. Warm mix asphalt: an overview. J Clean Prod 2012;24:76–84. https://doi.org/10.1016/j.jclepro.2011.11.053.
[84] Utlu Z, Hepbasli A, Turan M. Performance analysis and assessment of an industrial dryer in ceramic production. Dry Technol 2011;29:1792–813. https://doi.org/10.1080/07373937.2011.602921.
[85] European Comission. Energy saving in the brick and tile industry 1998. https://publications.europa.eu/en/publication-detail/-/publication/0d5e9ce7-0ebd-4186-b1b1-4a1a9f942cdb.
[86] Mujumdar AS. Handbook of Industrial Drying. 4th ed. CRC Press; 2014.
[87] Jensen AS. Drying in Superheated Steam under Pressure. NDC, Helsinki: Fifth Nord. Dry. Conf; 2011.
[88] Ma T, Wang Q, Chu W, Li X, Chen Y. Experimental investigation on SCO 2 -water heat transfer characteristics in a printed circuit heat exchanger with straight channels. Int J Heat Mass Transf 2017;113:184–94. https://doi.org/10.1016/j.ijheatmasstransfer.2017.05.059.
[89] Henrickson L. The need for energy efficiency in bayer refining. Light Met 2010:691–6.
[90] Saygin D, Patel M, Tam C, Gielen D. Chemical and Petrochemical sector. Potential of best practice technology and other measures for improving energy efficiency. IEA Inf Pap OECD/IEA 2009:1–60.
[91] Suhr M, Klein G, Kourti I, Rodrigo Gonzalo M, Giner Santonja G, Roudier S, et al. Best Available Techniques (BAT) reference document for the production of pulp Paper Board. JRC Sci Policy Rep 2015. https://doi.org/10.2791/370629.
[92] AG Energiebilanzen e.V. Auswertungstabellen zur Energiebilanz Deutschland. 1990 bis 2017 (Stand Juli 2018) 2018. https://www.ag-energiebilanzen.de/10-0-auswertungstabellen.html (accessed January 15, 2019).

Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C

Benjamin Zühlsdorf [1], *Fabian Bühler* [2], *Michael Bantle* [3], *Brian Elmegaard* [2]

[1] Danish Technological Institute, Energy and Climate, Aarhus C, Denmark, bez@dti.dk
[2] Technical University of Denmark, Department of Mechanical Engineering, Kgs. Lyngby, Denmark
[3] SINTEF Energi AS, Department of Thermal Energy, Trondheim, Norway

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Cascade multi-stage steam compression, Decarbonization, High-temperature heat pump, Process heat, Reversed Brayton cycle, R718, R744.

Introduction

The ambitions to reduce greenhouse gas emissions do inevitably require sustainable alternatives to fossil fuel-based combustions for supply of process heat to industrial processes. Electricity-driven heat pumps imply the general potential to operate emission free and do thereby represent a sustainable long-term solution for emission free process heat supply.

Currently available heat pump technologies are however limited to supply temperatures of 100 °C to 150 °C, while electric boilers and biomass boilers are often mentioned as alternatives in energy transition strategies. The overall feasibility for heat pump systems in such applications is among others limited by technical component constraints as well as limited thermodynamic performances, resulting in limited operating performances.

Zühlsdorf et al. [1] have therefore analyzed the possibilities for heat pump-based process heat supply at large capacities and temperatures above 150 °C. They evaluated the technical and economic feasibility of two heat pump systems for two case studies. The main results from [1] are summarized by this extended abstract. The article focused on large-scale applications and considered components as known from oil- and gas applications, as these are capable of operating in more challenging conditions and enable exceeding the limitations known from available refrigeration equipment [2]. In addition, the focus was on applications, in which the plant owners have access to electricity at low costs or the possibility to invest in own renewable electricity generators, such as wind farms and photovoltaics, as these are ensuring low levelized cost of electricity [3].

Methods

The study considered two different heat pump systems, namely a cascade multi-stage steam compression system and a reversed Brayton cycle. The cascade multi-stage steam compression system is shown in Figure 1 and consists of bottom cycles that are recovering the heat from the heat sources while providing heat to the evaporator of the top cycle, in which the steam from the evaporator is compressed in several stages. The steam is cooled by liquid injection after each compression stage. The system can supply steam at every pressure level to the system, ensuring an optimal integration into the process and thereby maximum performances.

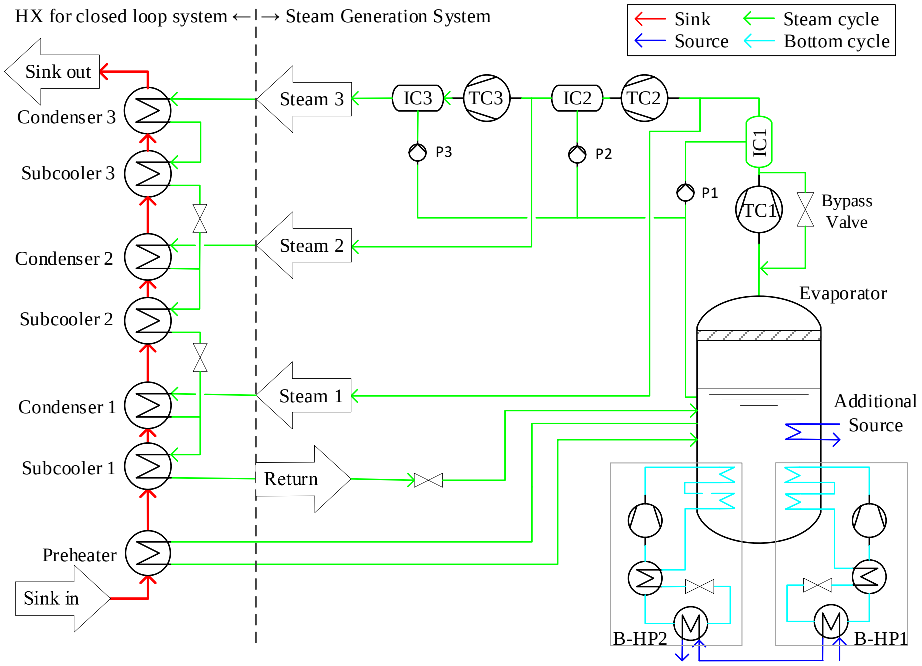

Figure 1: Flow sheet of a cascade heat pump with a multi-stage R-718 cycle for steam generation or closed loop heat supply at different temperature levels (B-HP = Bottom heat pump, IC = Intercooler, P = Pump, TC = Turbocompressor), [1]

The less complex layout of the reversed Brayton cycle is shown in Figure 2. The cycle consists of three heat exchangers, as well as a turbocompressor and a turboexpander, which are mounted on the same shaft. The cycle uses CO_2 as working fluid and operates completely in the gas phase.

The cycles were modelled with energy and mass balances. Design variables, such as pinch points in the heat exchangers or pressure levels were defined or optimized under consideration of common limitations. The investment cost of the equipment was estimated with cost correlations and validated with estimations obtained from manufacturers.

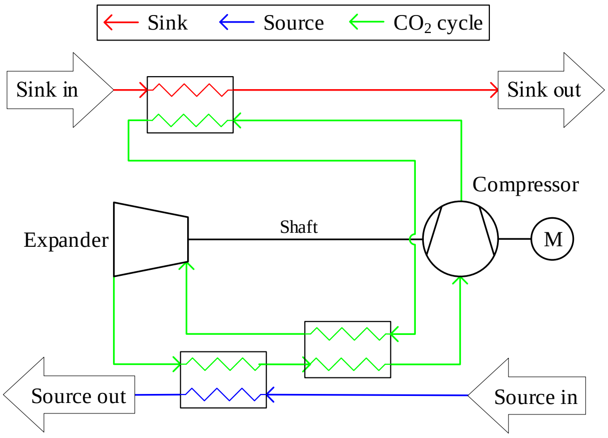

Figure 2: Flow sheet of reversed Brayton cycle, [1]

Both cycles were evaluated for two case studies. The first case study was alumina production in which 50 MW were supplied to heat thermal oil from 140 °C to 280 °C, while heat was recovered between 110 °C and 60 °C. The second case study was a spray dryer for milk powder production in which an air stream was heated up from 64 °C to 210 °C with a capacity of 8.2 MW, while a heat source at 50 °C was recovered.

Both technologies were evaluated in both cases for a set of economic boundary conditions. Three economic scenarios were considered that corresponded to the fuel cost in Norway, Germany and Denmark in 2020 and one scenario was considered corresponding to the acquisition and operation of own renewables.

Results

The heat pump systems were designed and optimized for both case studies. Table 1 shows the COP and the total capital investment TCI for both cases and both technologies. It may be seen that the COP for the cascade system was estimated to be 1.9 in both cases, while it was 1.7 for the reversed Brayton cycle in the alumina production and 1.6 in the spray dryer case. The investment cost were relatively similar for the two technologies, while the economy of scale yielded considerably lower specific investment cost for the alumina production.

Table 1: COP and Total capital investment TCI for both cases and cycles [1]

	Alumina production		Spray dryer	
	Cascade multi-stage system	Reversed Brayton cycle	Cascade multi-stage system	Reversed Brayton cycle
Coefficient of performance COP, -	1.92	1.72	1.92	1.61
Total capital investment TCI, Mio. €	47.3	48.3	16.4	15.4
Specific total capital investment TCI_{spec}, €/kW	946	966	1,997	1,868

Figure 3 shows the levelized cost of heat for both technologies and both case studies for all economic scenarios and compares them to the alternative heat supply technologies. The levelized cost of heat is divided into the contributions accounting for the investment, the fuel cost and an exemplifying CO_2 tax of 50 €/ton to indicate the impact of a potential tax. In the case of the alumina production, the levelized cost of heat reaches as low as 31 €/MWh to 33 €/MWh under consideration of own renewable electricity facilities, while it is between 44 €/MWh and 46 €/MWh for the spray dryer case. In the spray dryer case, the heat pump-based solutions are competitive with a biomass boiler and a natural gas boiler under consideration of the assumed CO_2 tax. In the alumina production case, the lowest levelized cost of heat are obtained for the heat pump systems.

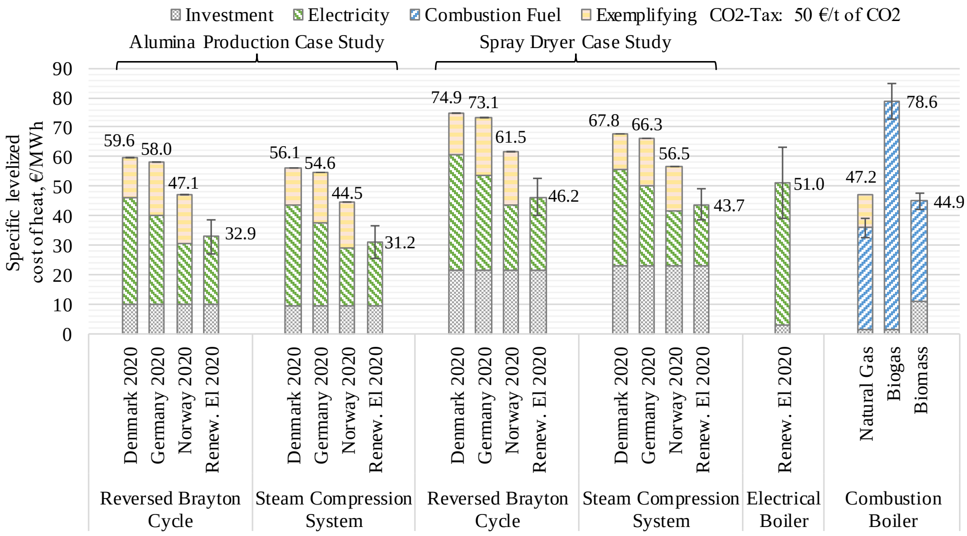

Figure 3: Specific levelized cost of heat c_h for both case studies including the reversed Brayton cycle, the multi-stage steam compression cycle, an electrical boiler and combustion-based boiler using natural gas, biogas and biomass. The cost scenarios are as defined in [1] *while the ranges for the cost for electricity from renewables, natural gas, biogas and biomass are indicated by the black bars* [1]

Conclusions

The study analyzed a reversed Brayton cycle and a cascade multi-stage steam compression for large-scale process heat supply at temperatures above 150 °C. It was pointed out that these temperatures might be reached by components from oil- and gas industries and that low electricity prices, as typically accessible for energy intensive industries or obtainable from acquiring and operating own renewable facilities, may improve the economic performance considerably. The levelized cost of heat for the heat pump-based systems were competitive to the biomass boilers and natural gas boilers for the spray dryer case study and outperformed both for the alumina production case study. This study has accordingly demonstrated, that heat pump systems are a viable alternative for process heat supply in industrial processes at temperatures of up to 280 °C.

References

[1] Zühlsdorf B, Bühler F, Bantle M, Elmegaard B. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C. Energy Conversion and Management: X 2019;2:100011. doi:10.1016/j.ecmx.2019.100011.

[2] Aga V, Conte E, Carroni R, Burcker B, Ramond M. Supercritical CO2-Based Heat Pump Cycle for Electrical Energy Storage for Utility Scale Dispatchable Renewable Energy Power Plants. The 5th International Supercritical CO2 Power Cycles Symposium, San Antonio, Texas: 2016.

[3] Philibert C. Renewable Energy for Industry - From green energy to green materials and fuels. International Energy Agency 2017:72. https://www.iea.org/publications/insights/insightpublications/Renewable_Energy_for_Industry.pdf (accessed January 15, 2019).


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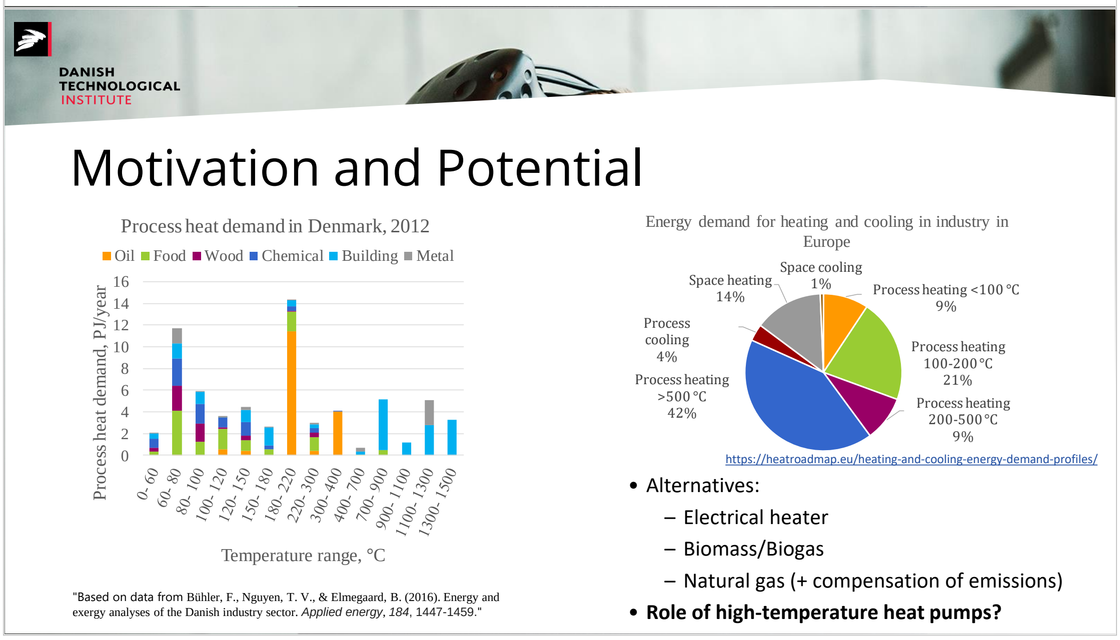
Benjamin Zühlsdorf, F. Bühler, M. Bantle, B. Elmegaard
bez@teknologisk.dk, +45 7220 1258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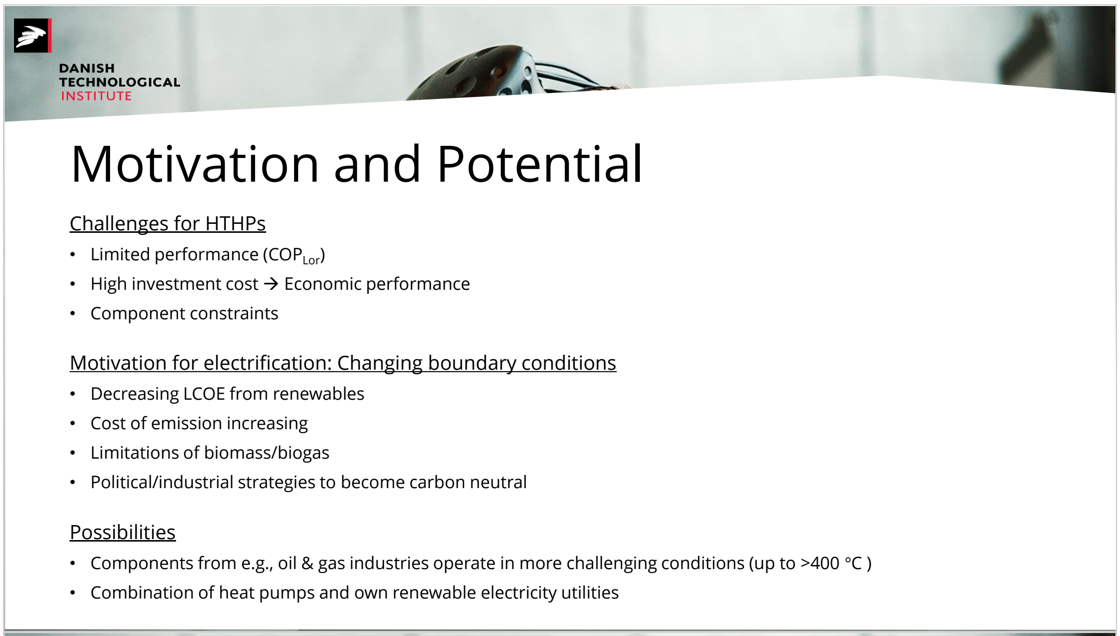
Motivation and Potential
Process heat demand in Denmark, 2012
Oil
Food
Wood
Chemical
Building
Metal
Process heat demand, PJ/year
Temperature range, °C
"Based on data from Bühler, F., Nguyen, T. V., & Elmegaard, B. (2016). Energy and exergy analyses of the Danish industry sector. Applied energy, 184, 1447-1459."
Energy demand for heating and cooling in industry in Europe
Space cooling 1%
Space heating 14%
Process heating <100 °C 9%
Process cooling 4%
Process heating 100-200 °C 21%
Process heating >500 °C 42%
Process heating 200-500 °C 9%
https://heatroadmap.eu/heating-and-cooling-energy-demand-profiles/
Alternatives:
Electrical heater
Biomass/Biogas
Natural gas (+ compensation of emissions)
Role of high-temperature heat pumps?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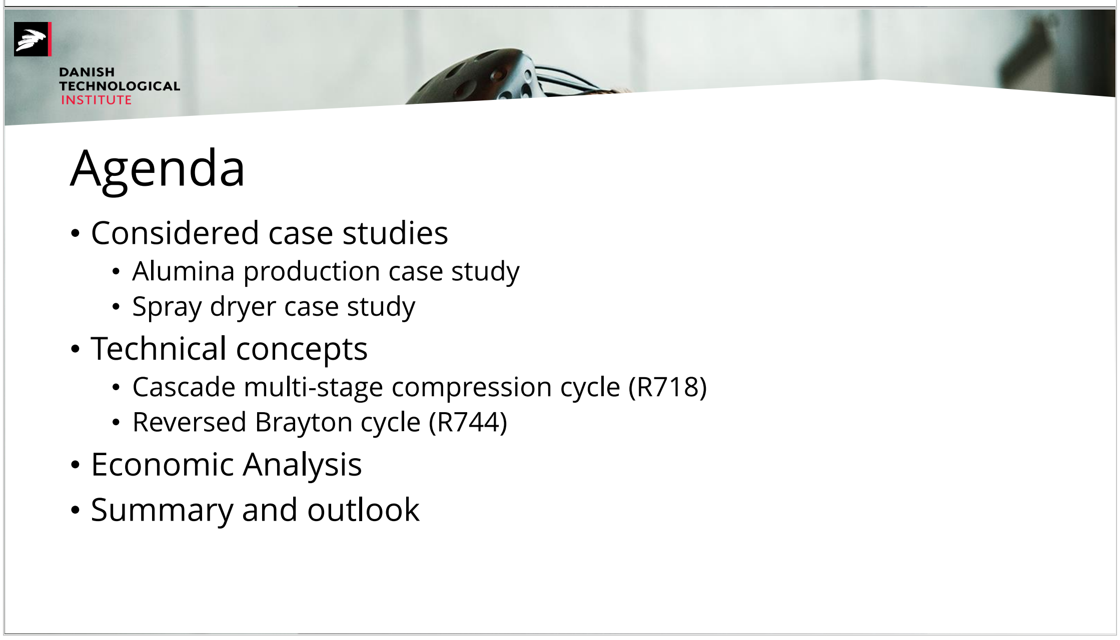
Motivation and Potential
Challenges for HTHPs
• Limited performance (COP_{Lor})
• High investment cost → Economic performance
• Component constraints
Motivation for electrification: Changing boundary conditions
• Decreasing LCOE from renewables
• Cost of emission increasing
• Limitations of biomass/biogas
• Political/industrial strategies to become carbon neutral
Possibilities
• Components from e.g., oil & gas industries operate in more challenging conditions (up to >400 °C)
• Combination of heat pumps and own renewable electricity utilities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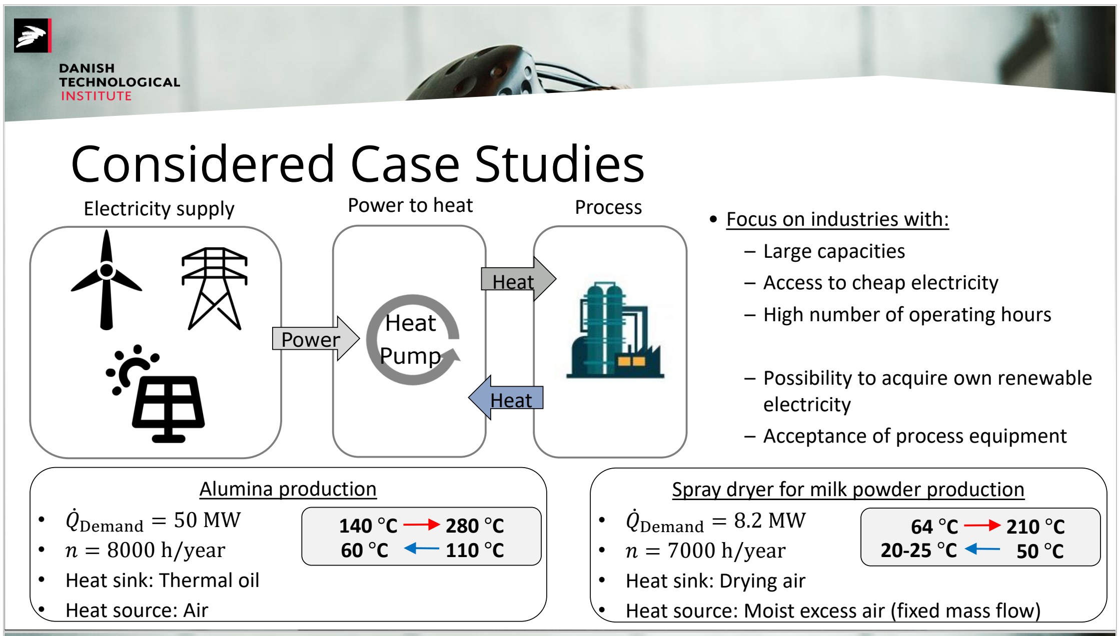
Agenda
• Considered case studies
• Alumina production case study
• Spray dryer case study
• Technical concepts
• Cascade multi-stage compression cycle (R718)
• Reversed Brayton cycle (R744)
• Economic Analysis
• Summary and outlook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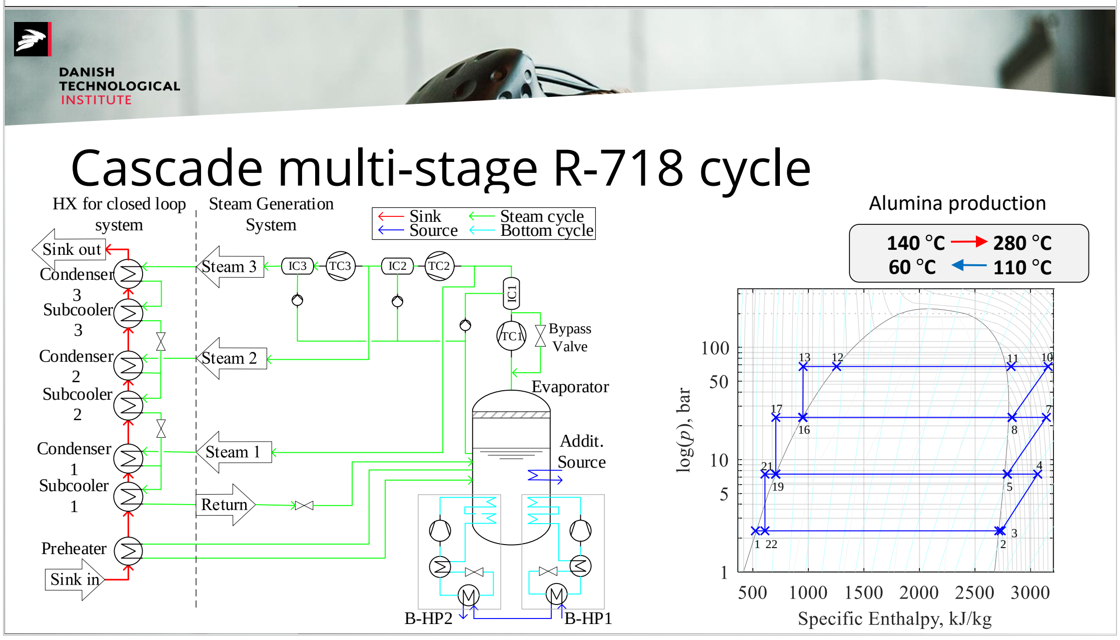
Considered Case Studies
Electricity supply
Power to heat
Process
Power
Heat Pump
Heat
Heat
• Focus on industries with:
– Large capacities
– Access to cheap electricity
– High number of operating hours
– Possibility to acquire own renewable electricity
– Acceptance of process equipment
Alumina production
• $\dot{Q}_{\text{Demand}} = 50$ MW
• $n = 8000$ h/year
• Heat sink: Thermal oil
• Heat source: Air
140 °C → 280 °C
60 °C ← 110 °C
Spray dryer for milk powder production
• $\dot{Q}_{\text{Demand}} = 8.2$ MW
• $n = 7000$ h/year
• Heat sink: Drying air
• Heat source: Moist excess air (fixed mass flow)
64 °C → 210 °C
20-25 °C ← 50 °C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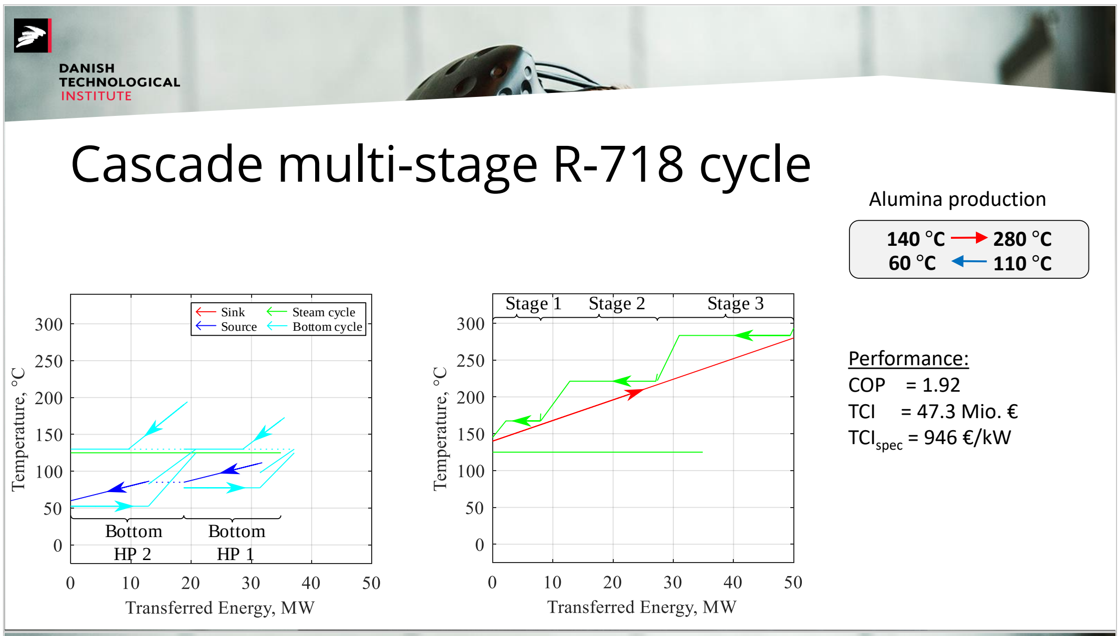
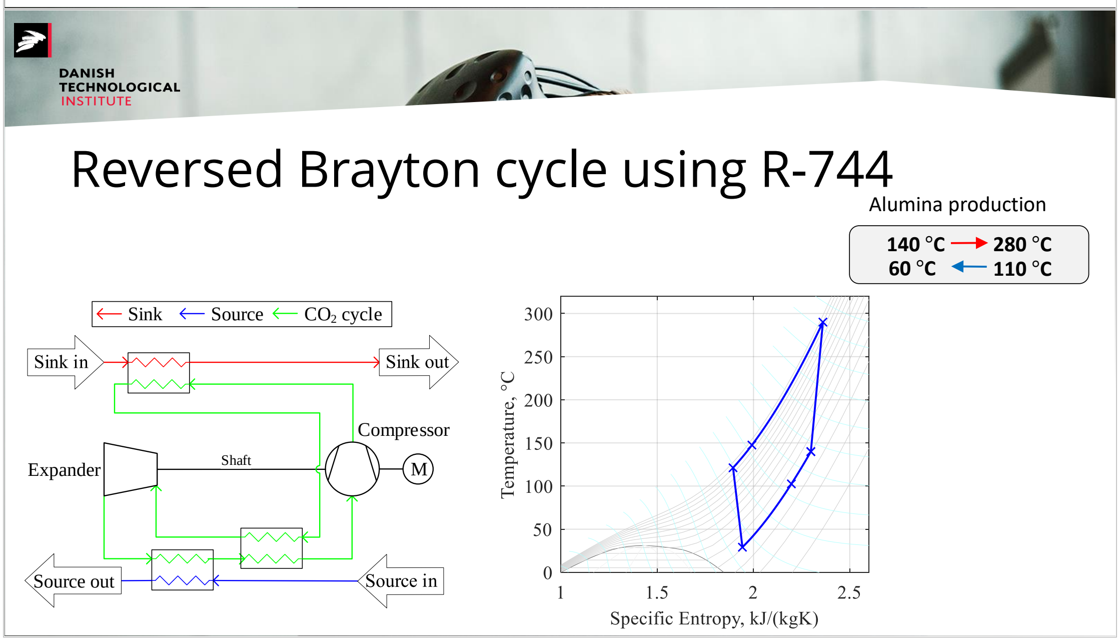
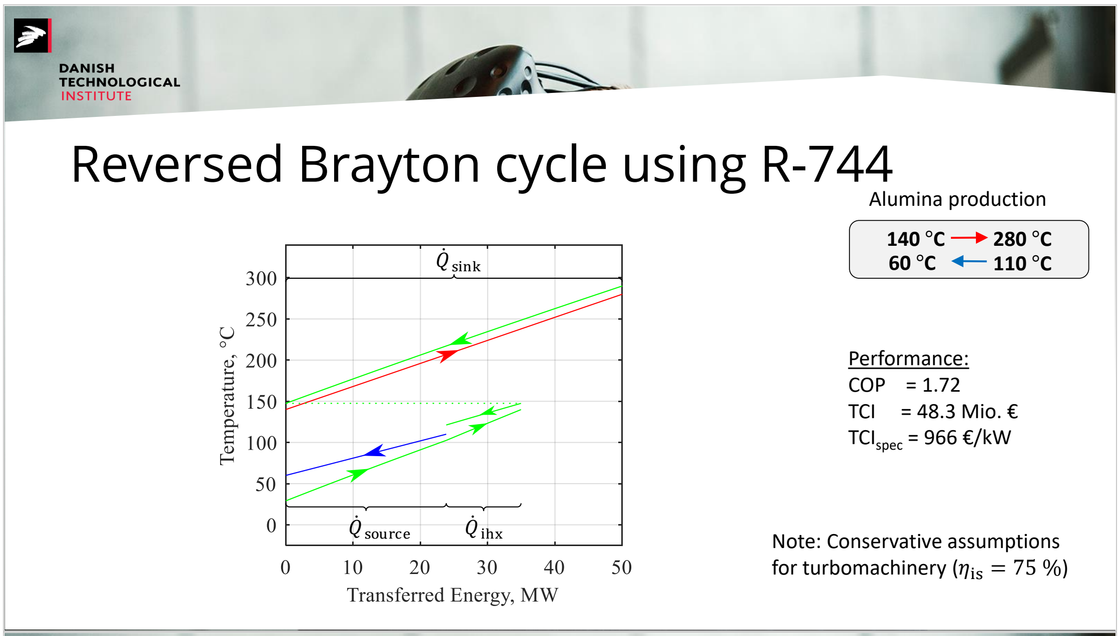
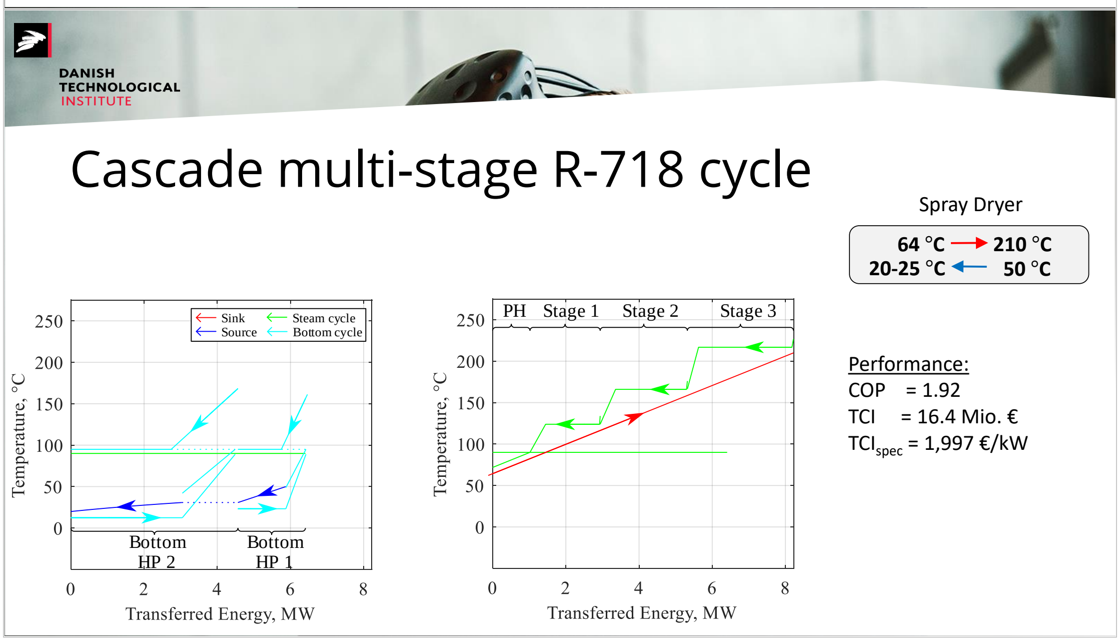
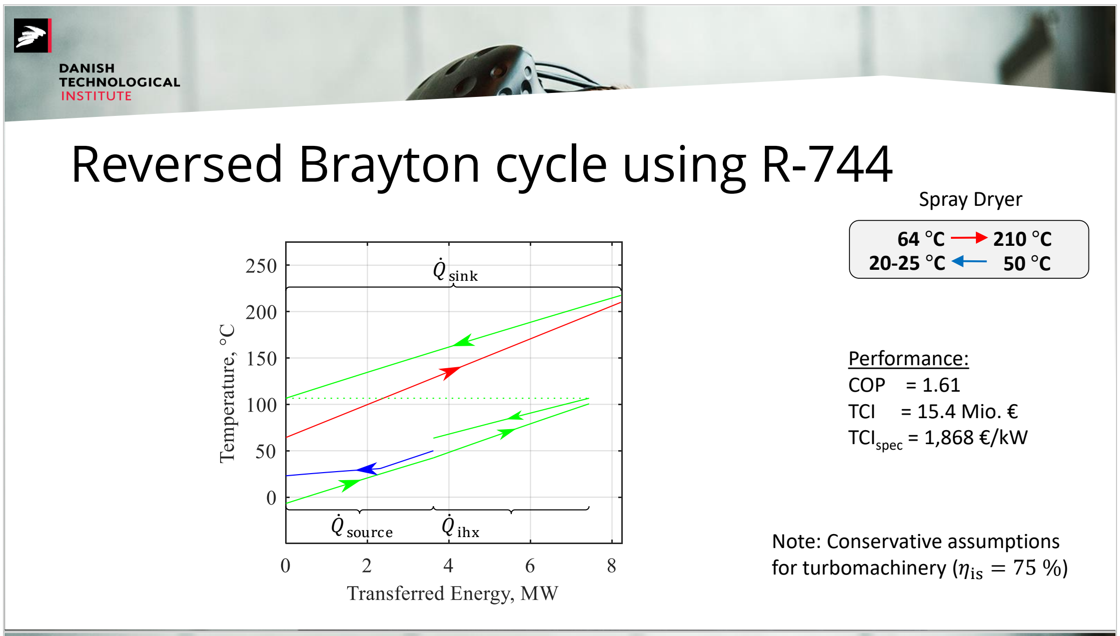
Cascade multi-stage R-718 cycle
HX for closed loop system
Steam Generation System
Sink
Source
Steam cycle
Bottom cycle
Sink out
Condenser 3
Subcooler 3
Condenser 2
Subcooler 2
Condenser 1
Subcooler 1
Preheater
Sink in
Steam 3
Steam 2
Steam 1
Return
IC3
TC3
IC2
TC2
IC1
TC1
Bypass Valve
Evaporator
Addit. Source
B-HP2
B-HP1
Alumina production
140 °C → 280 °C
60 °C ← 110 °C
log(p), bar
Specific Enthalpy, kJ/kg

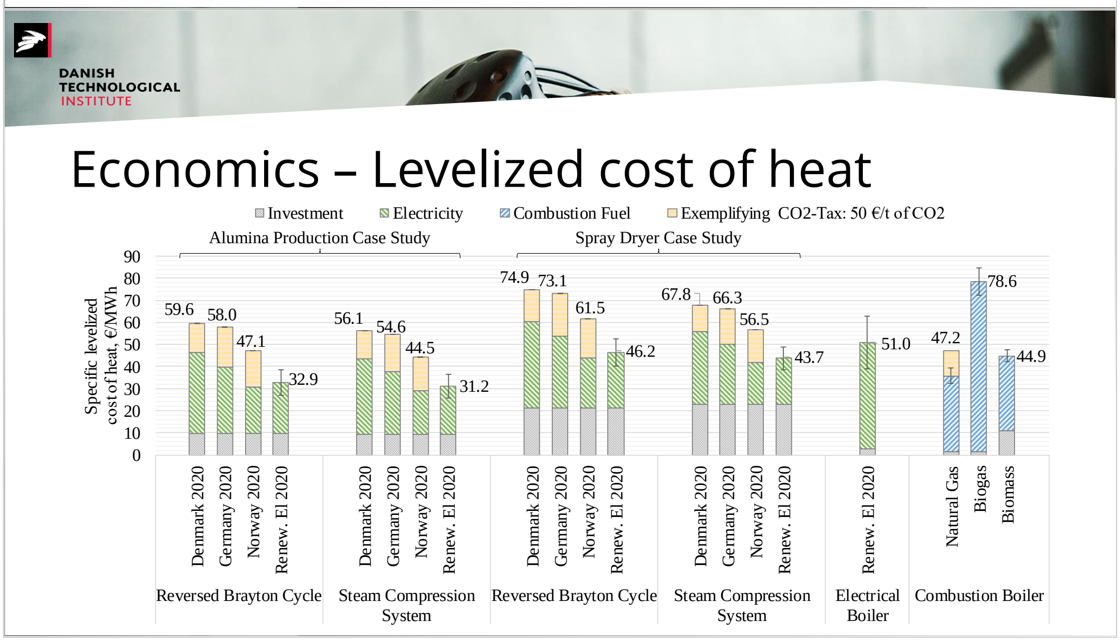

DANISH
TECHNOLOGICAL
INSTITUTE
Cascade multi-stage R-718 cycle
Alumina production
140 °C → 280 °C
60 °C ← 110 °C
Sink
Source
Steam cycle
Bottom cycle
Temperature, °C
Bottom HP 2
Bottom HP 1
Transferred Energy, MW
Stage 1
Stage 2
Stage 3
Temperature, °C
Transferred Energy, MW
Performance:
COP = 1.92
TCI = 47.3 Mio. €
TCI_spec = 946 €/kW

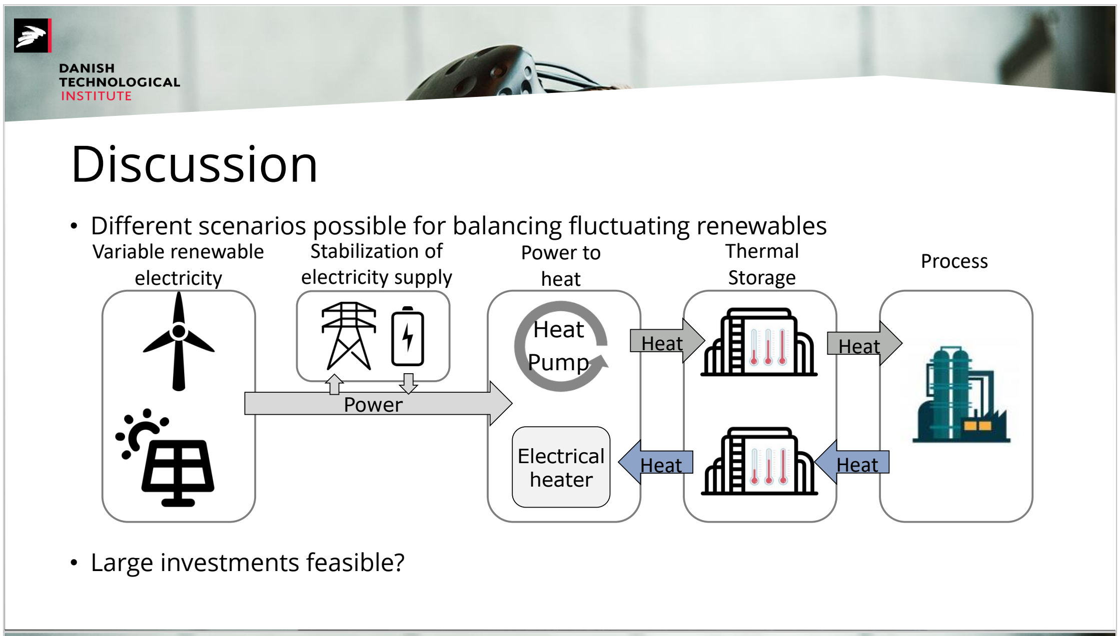

DANISH
TECHNOLOGICAL
INSTITUTE
Reversed Brayton cycle using R-744
Alumina production
140 °C → 280 °C
60 °C ← 110 °C
Sink
Source
CO2 cycle
Sink in
Sink out
Compressor
Expander
Shaft
M
Source out
Source in
Temperature, °C
Specific Entropy, kJ/(kgK)

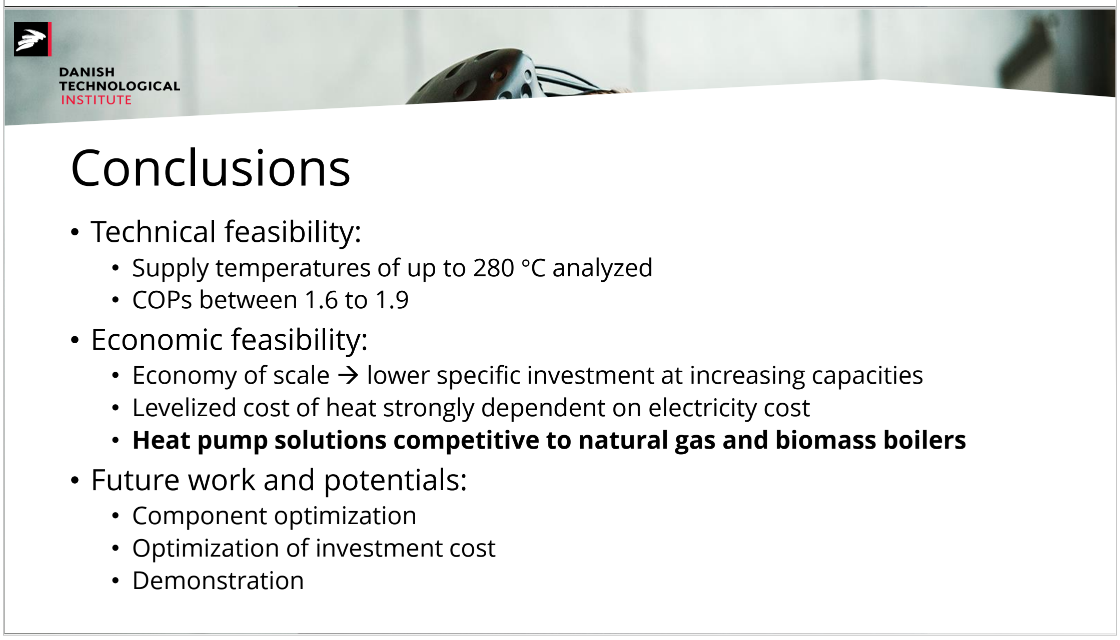

DANISH TECHNOLOGICAL INSTITUTE
Reversed Brayton cycle using R-744
Alumina production
140 °C → 280 °C
60 °C ← 110 °C
$\dot{Q}_{sink}$
$\dot{Q}_{source}$
$\dot{Q}_{ihx}$
Temperature, °C
Transferred Energy, MW
Performance:
COP = 1.72
TCI = 48.3 Mio. €
TCI_{spec} = 966 €/kW
Note: Conservative assumptions for turbomachinery (η_{is} = 75 %)


DANISH TECHNOLOGICAL INSTITUTE
Cascade multi-stage R-718 cycle
Spray Dryer
64 °C → 210 °C
20-25 °C ← 50 °C
Sink
Source
Steam cycle
Bottom cycle
Bottom HP 2
Bottom HP 1
PH
Stage 1
Stage 2
Stage 3
Temperature, °C
Transferred Energy, MW
Performance:
COP = 1.92
TCI = 16.4 Mio. €
TCI_{spec} = 1,997 €/kW


DANISH
TECHNOLOGICAL
INSTITUTE
Reversed Brayton cycle using R-744
Spray Dryer
64 °C → 210 °C
20-25 °C ← 50 °C
Temperature, °C
Transferred Energy, MW
$\dot{Q}_{sink}$
$\dot{Q}_{source}$
$\dot{Q}_{ihx}$
Performance:
COP = 1.61
TCI = 15.4 Mio. €
TCI_{spec} = 1,868 €/kW
Note: Conservative assumptions
for turbomachinery (η_{is} = 75 %)


DANISH
TECHNOLOGICAL
INSTITUTE
Economics – Levelized cost of heat
Investment
Electricity
Combustion Fuel
Exemplifying CO2-Tax: 50 €/t of CO2
Alumina Production Case Study
Spray Dryer Case Study
Specific levelized cost of heat, €/MWh
59.6
58.0
47.1
32.9
56.1
54.6
44.5
31.2
74.9
73.1
61.5
46.2
67.8
66.3
56.5
43.7
51.0
47.2
78.6
44.9
Denmark 2020
Germany 2020
Norway 2020
Renew. El 2020
Natural Gas
Biogas
Biomass
Reversed Brayton Cycle
Steam Compression System
Electrical Boiler
Combustion Boiler


DANISH
TECHNOLOGICAL
INSTITUTE
Discussion
• Different scenarios possible for balancing fluctuating renewables
Variable renewable electricity
Stabilization of electricity supply
Power to heat
Thermal Storage
Process
Power
Heat Pump
Electrical heater
Heat
Heat
Heat
Heat
• Large investments feasible?


DANISH
TECHNOLOGICAL
INSTITUTE
Conclusions
• Technical feasibility:
• Supply temperatures of up to 280 °C analyzed
• COPs between 1.6 to 1.9
• Economic feasibility:
• Economy of scale → lower specific investment at increasing capacities
• Levelized cost of heat strongly dependent on electricity cost
• Heat pump solutions competitive to natural gas and biomass boilers
• Future work and potentials:
• Component optimization
• Optimization of investment cost
• Demonstration

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

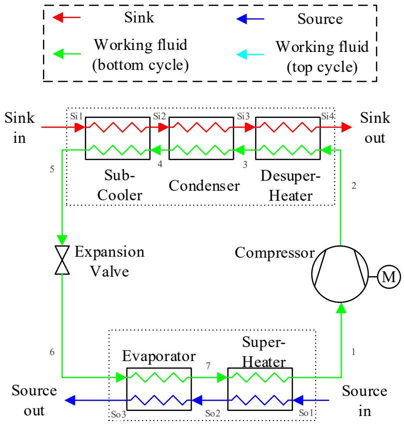
(for each case study:)

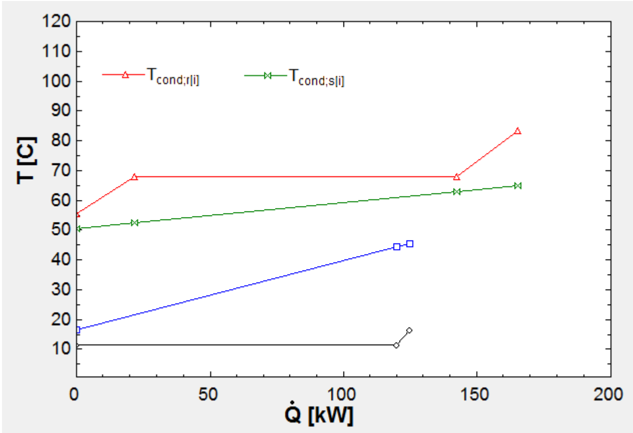
- Case Description
- Electrification Scenarios
- Energy analysis
- Economic analysis

Method
Overall Approach

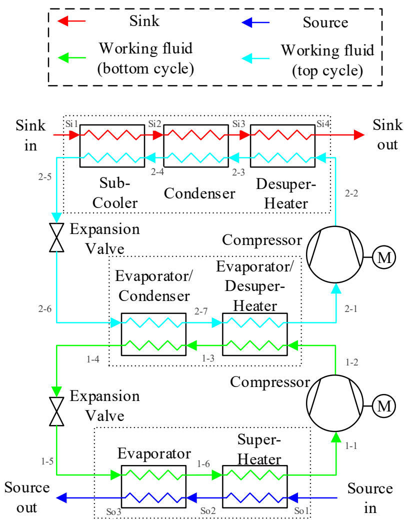
- Data collection and energy mapping
- Thermodynamic models of existing system
- Energy (and exergy) analysis
- Energy optimization (waste heat recovery and process integration)
- Electrification
  - Heat Pump integration
  - Central electrification
- Economic analysis
- Sensitivity analysis

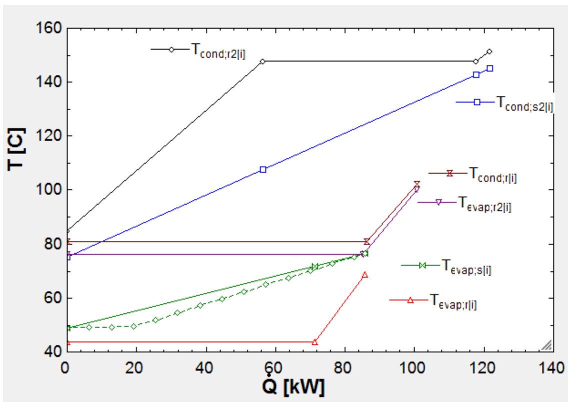
Continuous Tunnel Washer
Single Stage Heat Pump



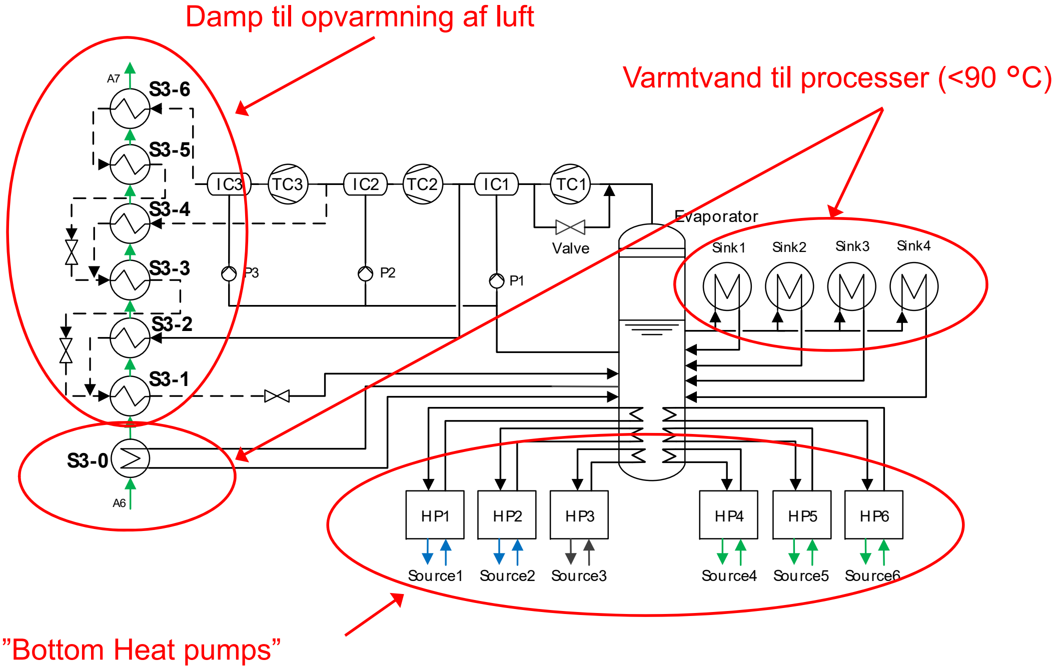


Method
Two Stage Heat Pump



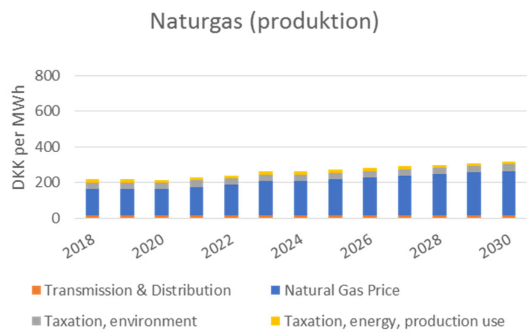


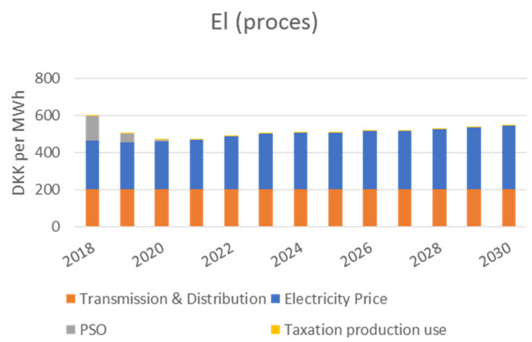
Method
Central Varmepumpe



Economic analysis electrification laundry
Investment Assumptions

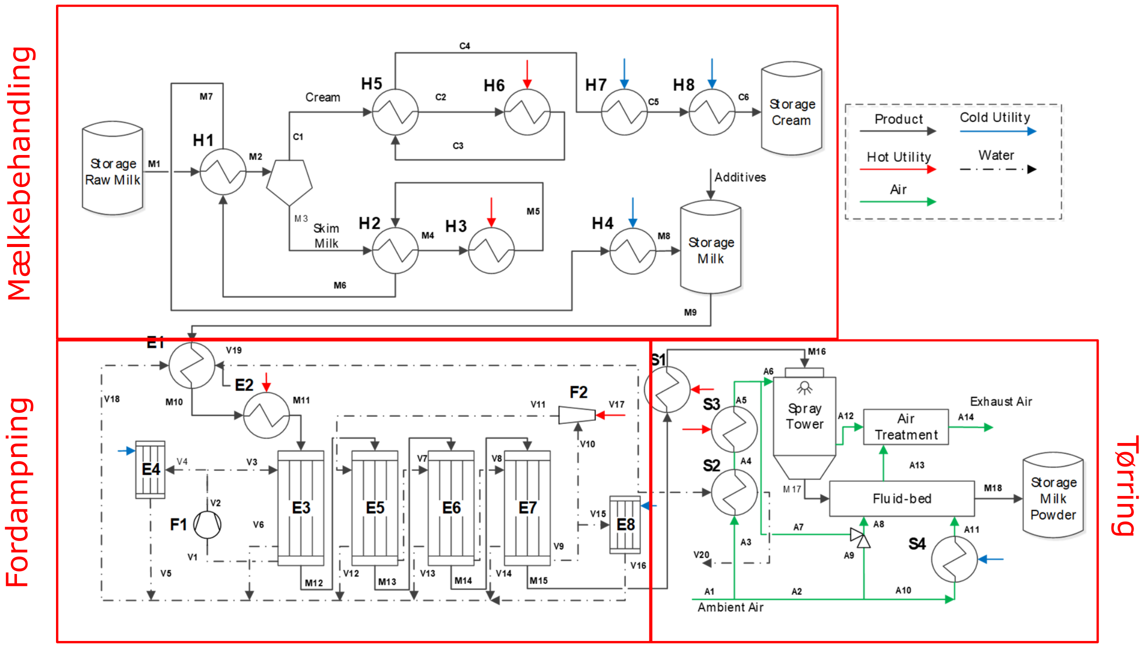
- Lifetime of investment 20 years
- Total module costs incl. auxiliary facilities and grasroot factor
- Inflation 2 % p.a.
- Discount rate 5 % p.a.
- Boiler efficiency 94 %
- Steam transmission and distribution efficiency 90 %





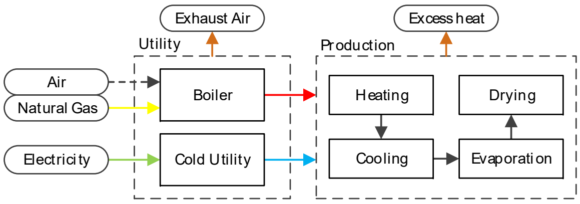
Case Study
Milk Powder Production

Milk powder case study
Process flow diagram

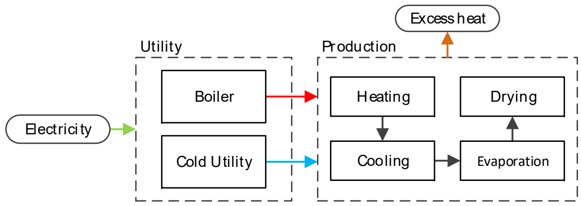


Milk powder case study
Strategier til elektrificere

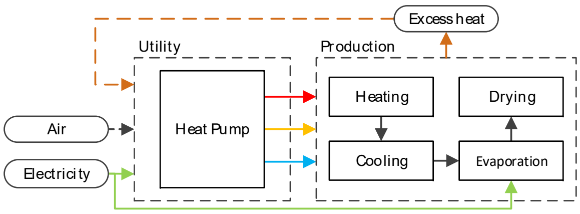
BAU



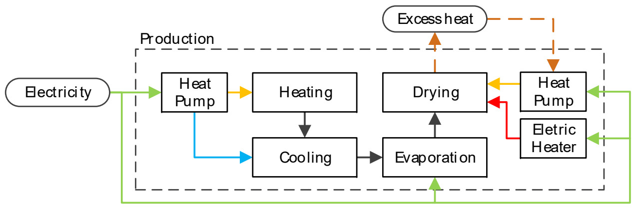
BAU – Elektrisk + energioptimering



Central Varmepumpe



Decentral Varmepumper

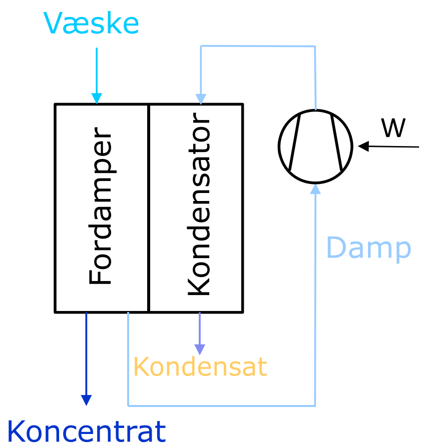


Milk powder case study
Muligheder

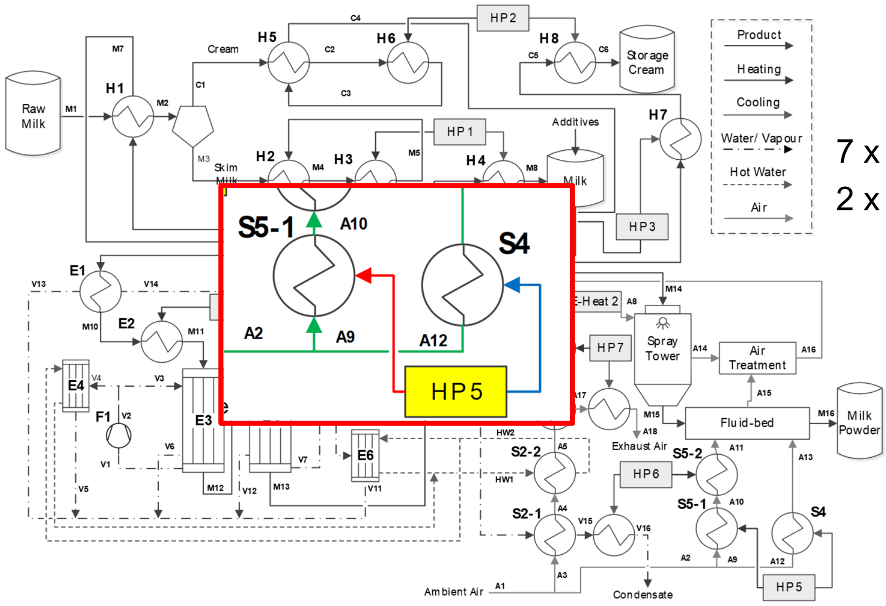
Energieffektivisering
- Varmegenvinding på kondenser
- Luftforvarmning med tørringsluft

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

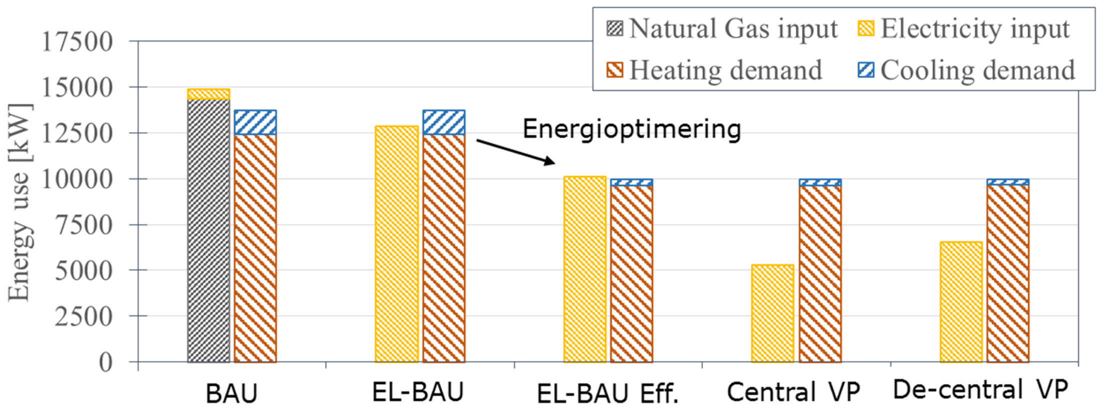


Milk powder case study
Decentral Varmepumper + Elpatron



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

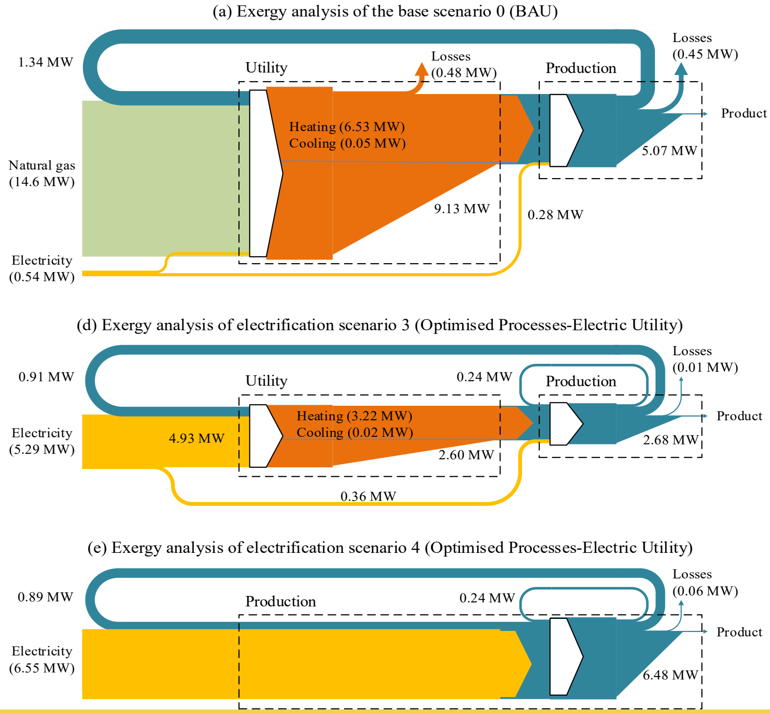
DTU

Milk powder case study
Resultater Exergi

BAU

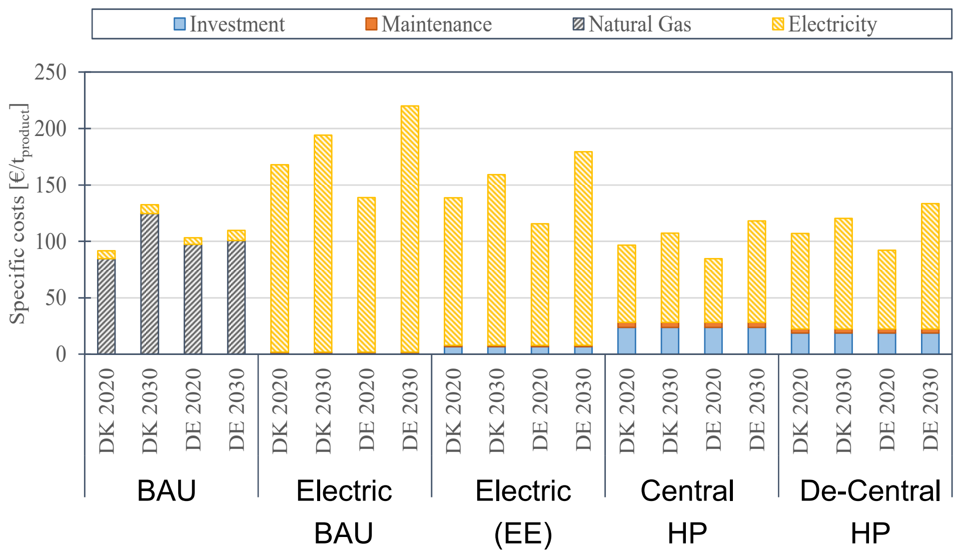
Central HP

De-Central HP

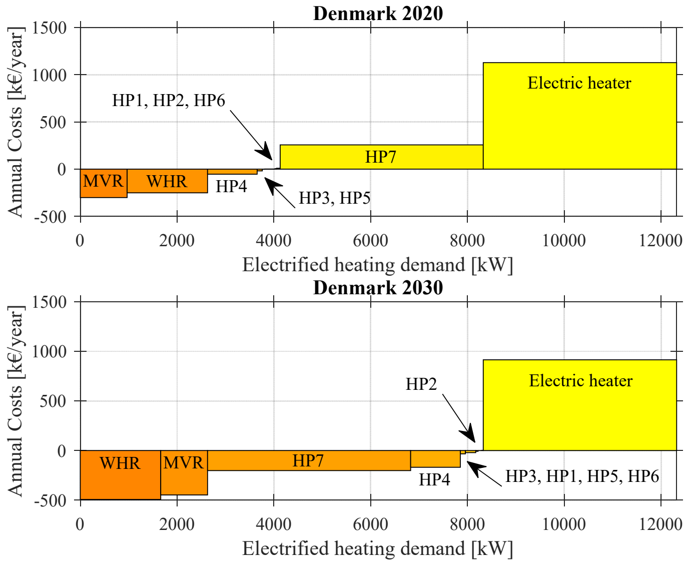


DTU

Milk powder case study
Resultater Økonomi



Milk powder case study
Resultater Økonomi



Energy integration and electrification opportunities in industrial laundries

Fabian Bühler [a], Fridolin Müller Holm [b], Benjamin Zühlsdorf [c] and Brian Elmegaard [d]

[a] *Technical University of Denmark, Kgs. Lyngby, Denmark, fabuhl@mek.dtu.dk*
[b] *Viegand Maagøe A/S, Copenhagen, Denmark, fmh@viegandmaagoe.dk*
[c] *Danish Technological Institute, Aarhus, Denmark, bez@dti.dk*
[d] *Technical University of Denmark, Kgs. Lyngby, Denmark,, be@mek.dtu.dk*

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.

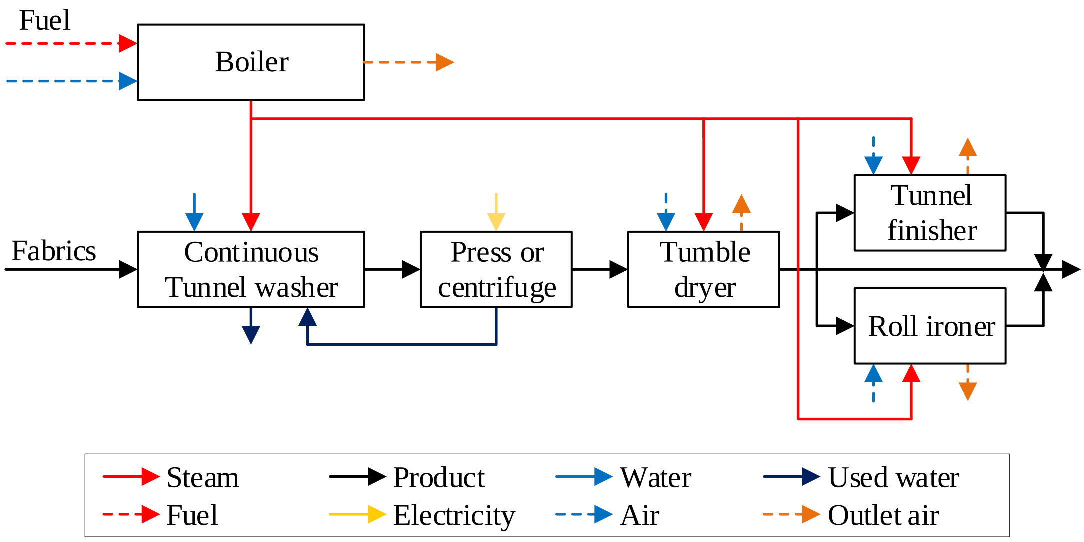


Fig. 1: Process description of the industrial laundry.

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.

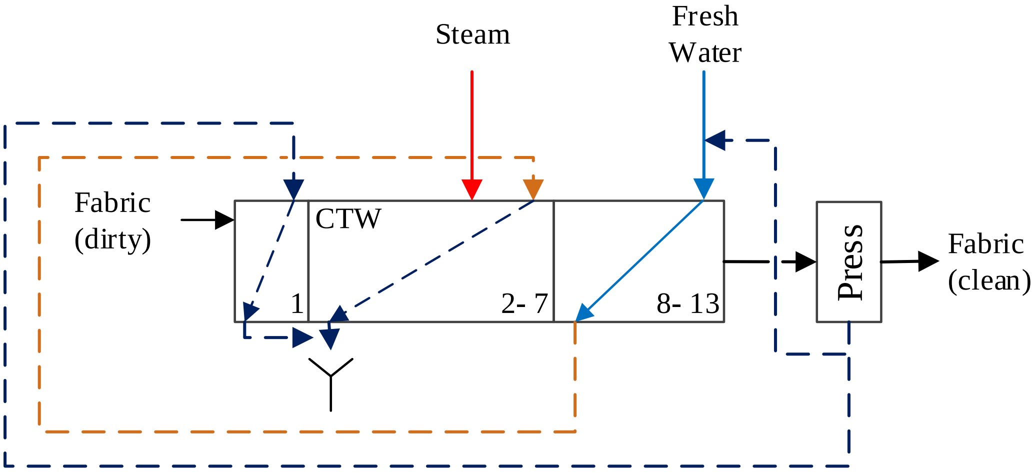


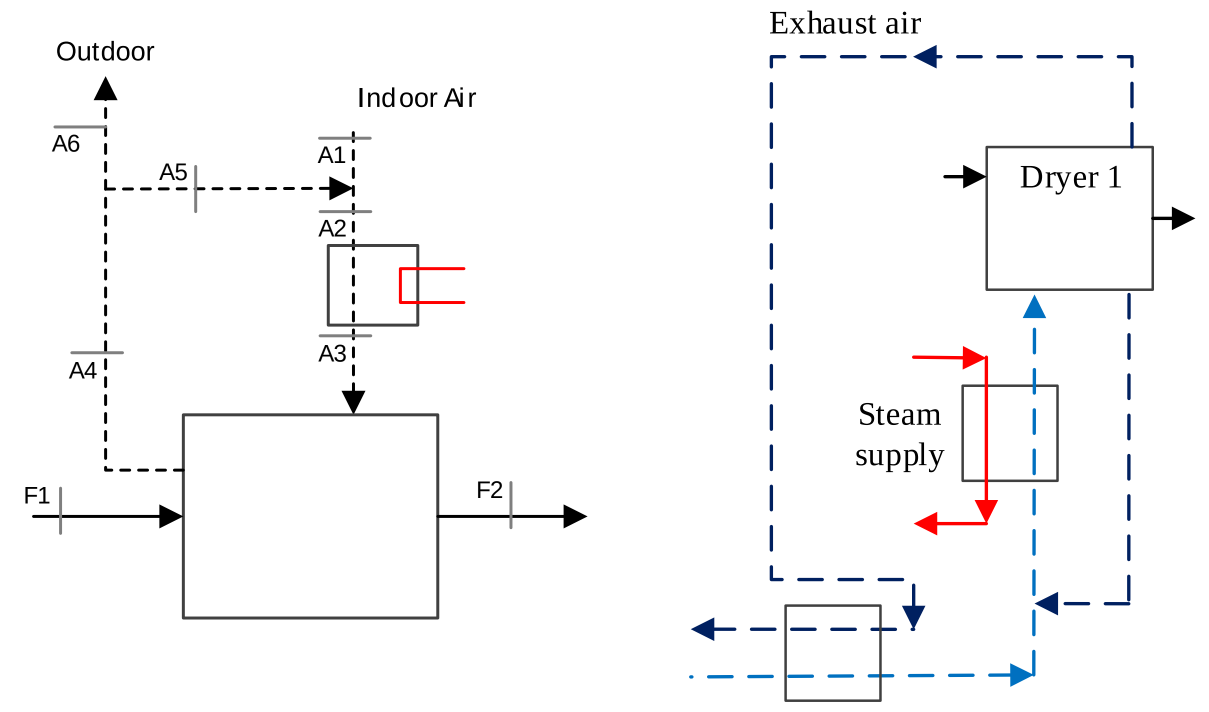
Fig. 2: Process description of the continuous tunnel washer (CTW).

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)

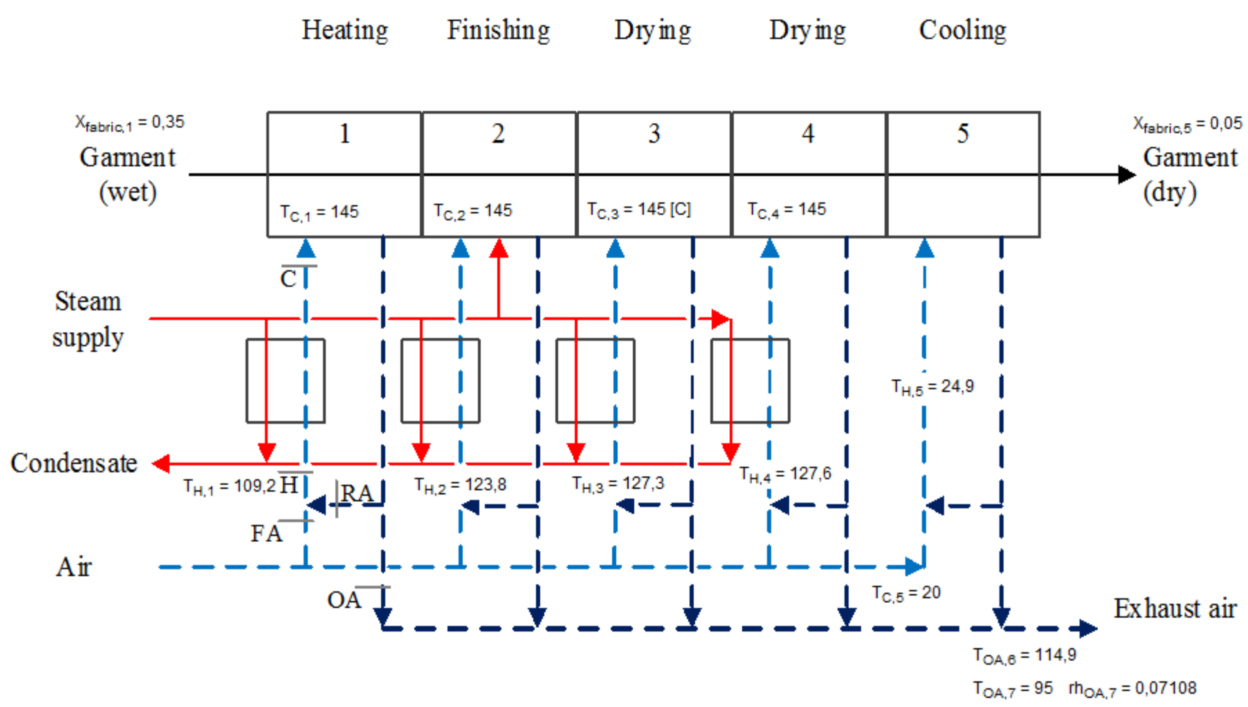


Fig. 4. Schematic of the tunnel finisher with the main temperature set-points (T) in °C, water content of the fabric (X) in kg/kg and relative humidity of the air (rh).

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).

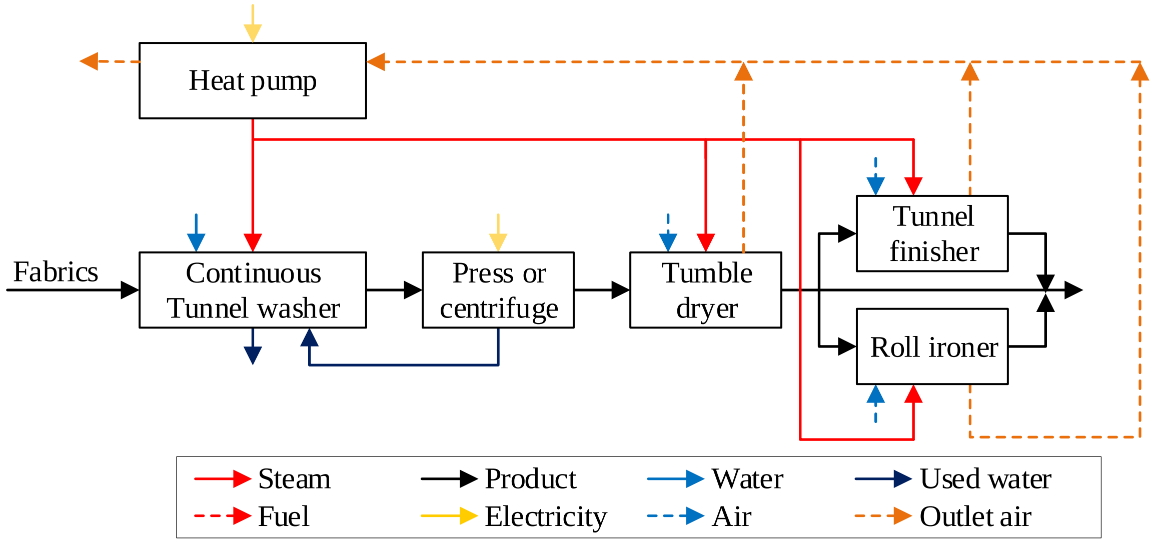


Fig. 5. Central electrification strategy of the laundry based on central steam generating heat pump.

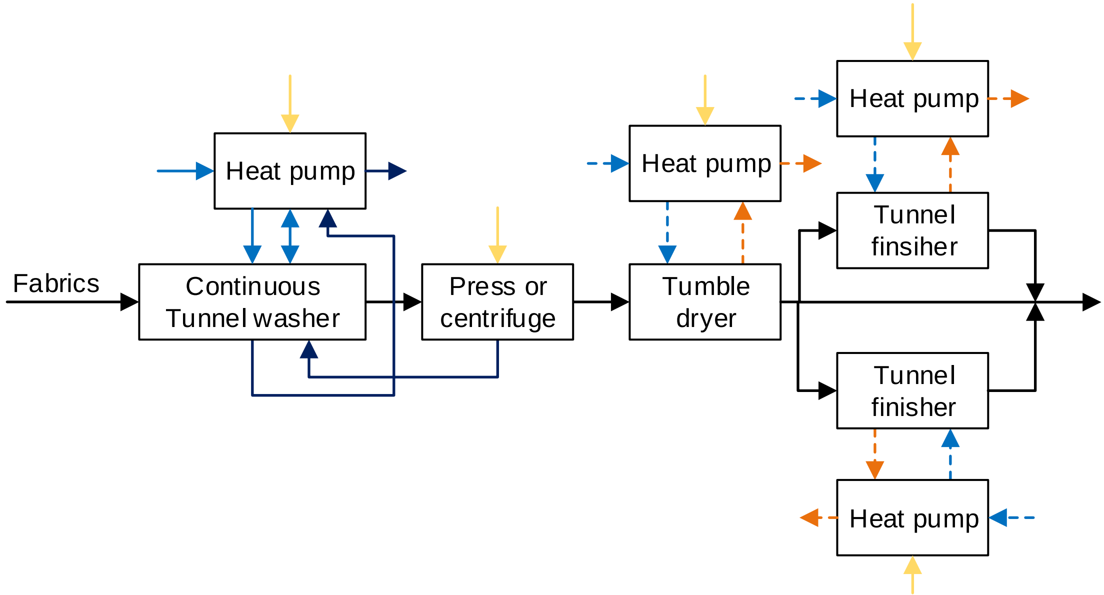


Fig. 6. Decentral electrification strategy of the laundry.

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.

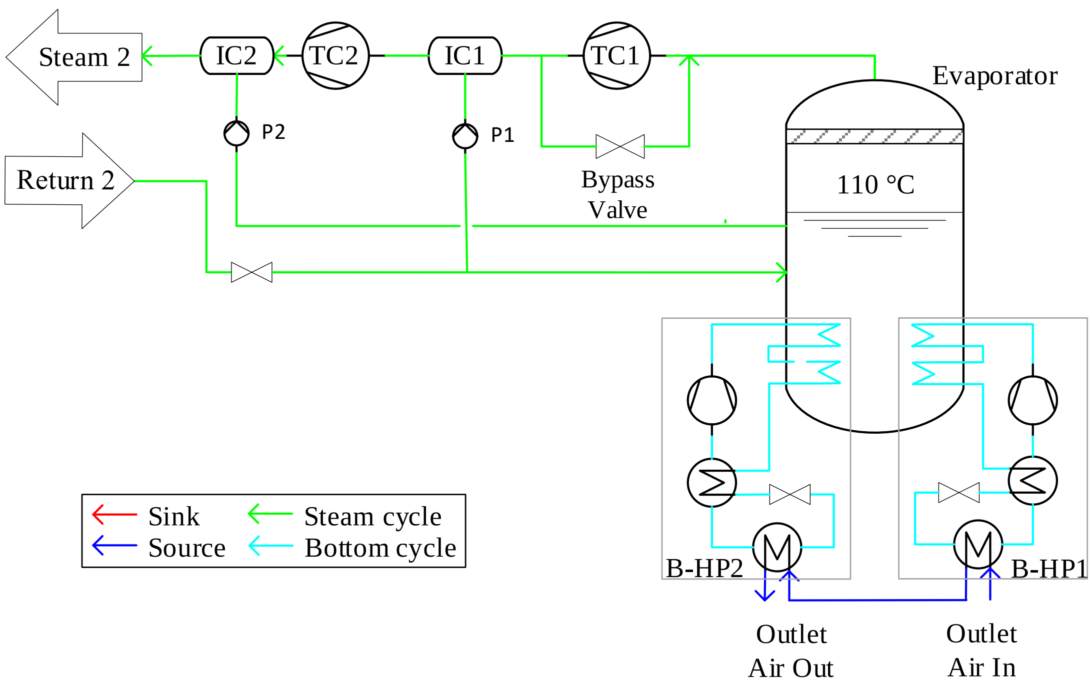


Fig. 7. Steam generation heat pump in multistage cascade system.

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.

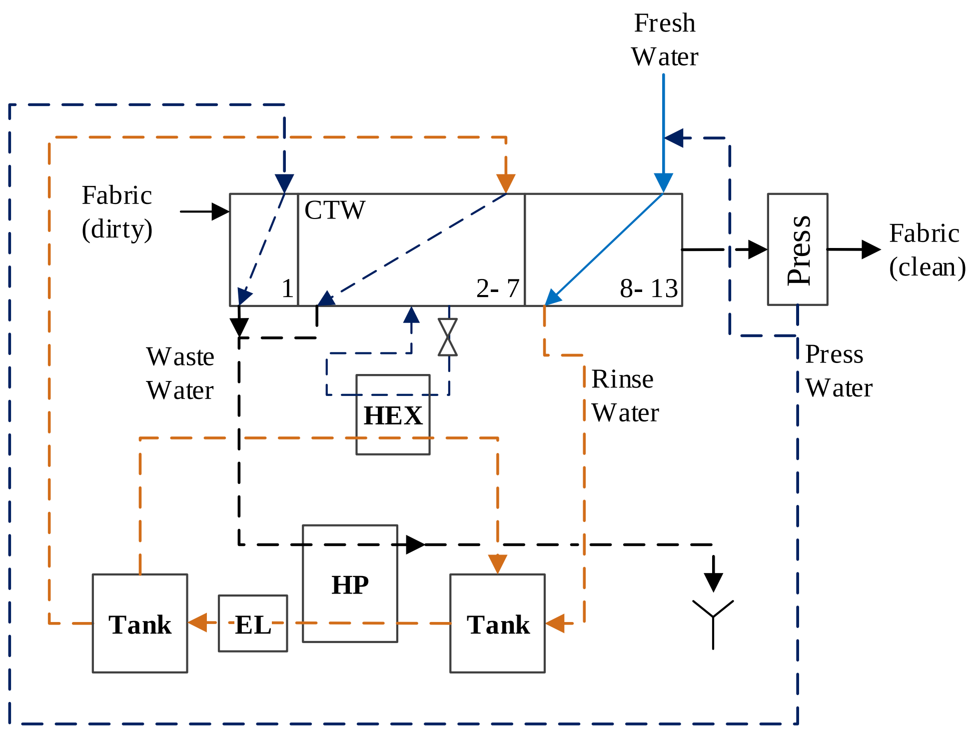


Fig. 8: Electrification of the CTW with waste heat recovery.

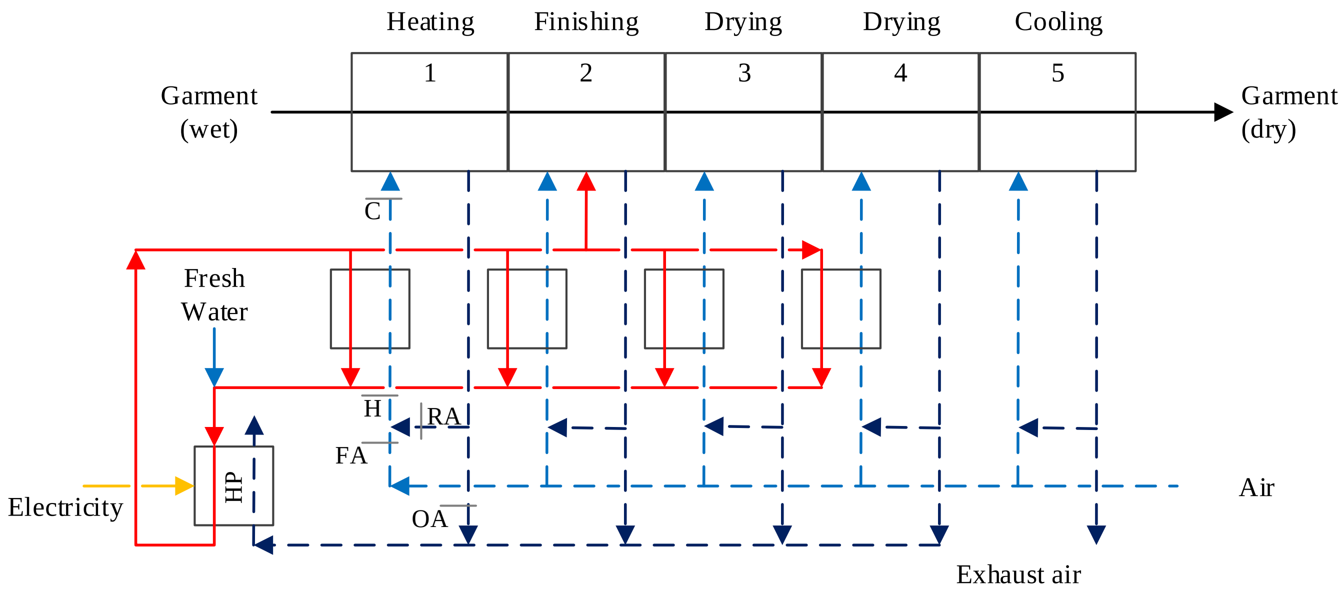


Fig. 9: Electrification of the tunnel finisher with waste heat recovery.

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.

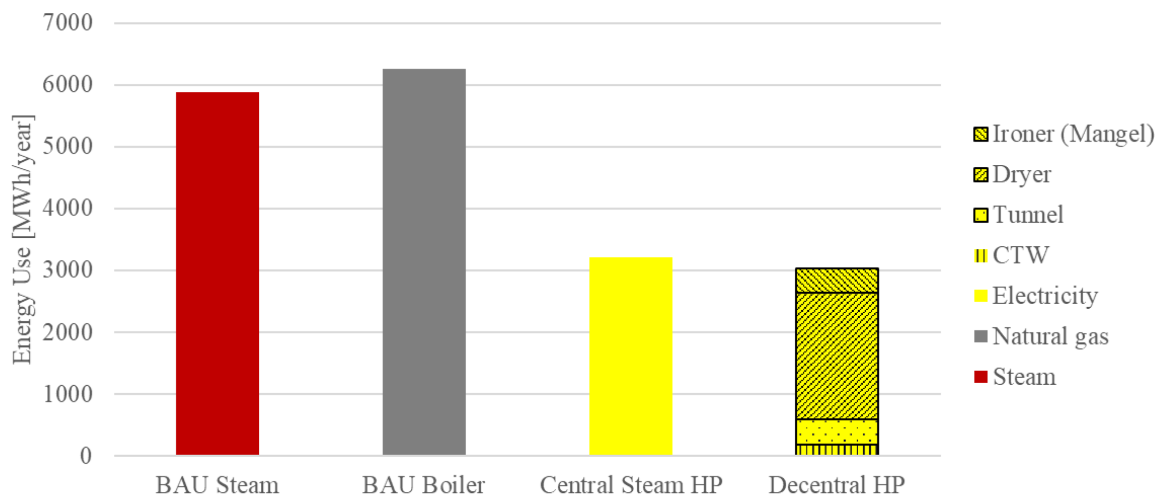


Fig. 10: Summary of the energy use before electrification (BAU) and after electrification for the central and decentral solution.

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.

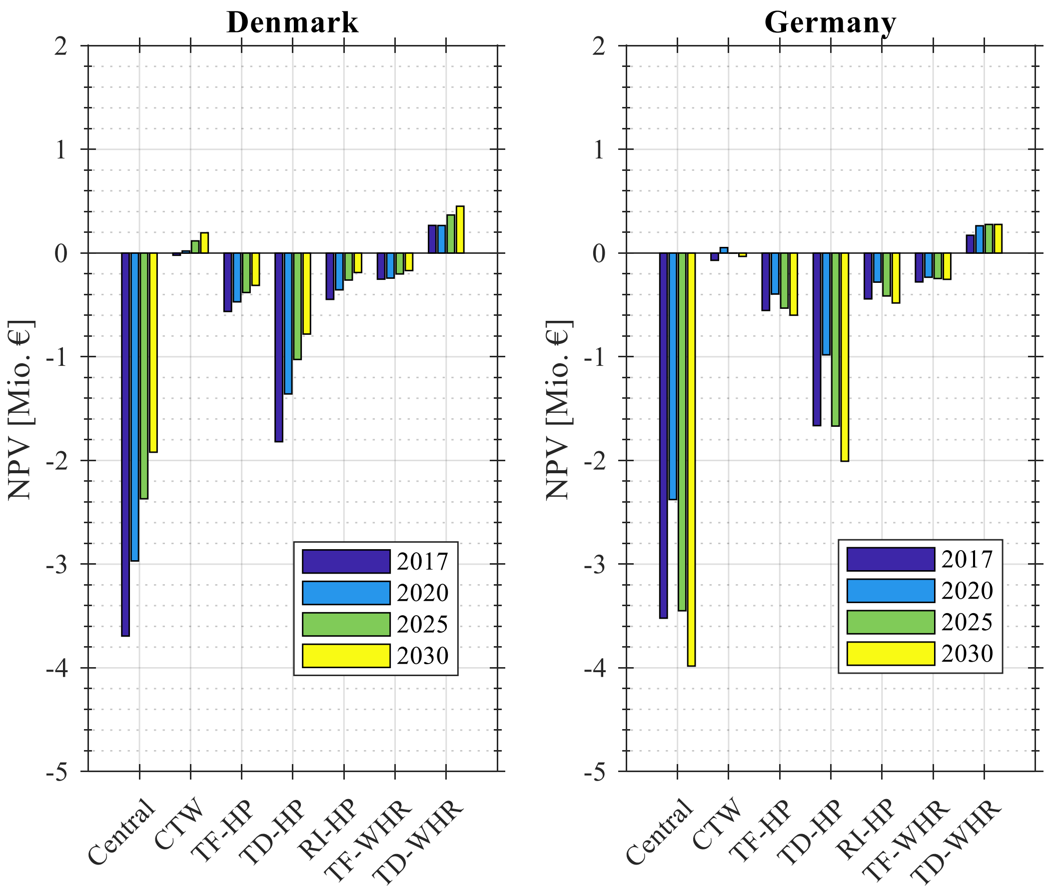


Fig. 11: Net Present Value for investments in central electrification (Central), the decentral electrification (CTW-Continuous Tunnel Waster, TF- Tunnel Finisher, TD – Tumble Dryer and RI – Roll Ironer) and alternative waste heat recovery (WHR) for the TF and TD without electrification.

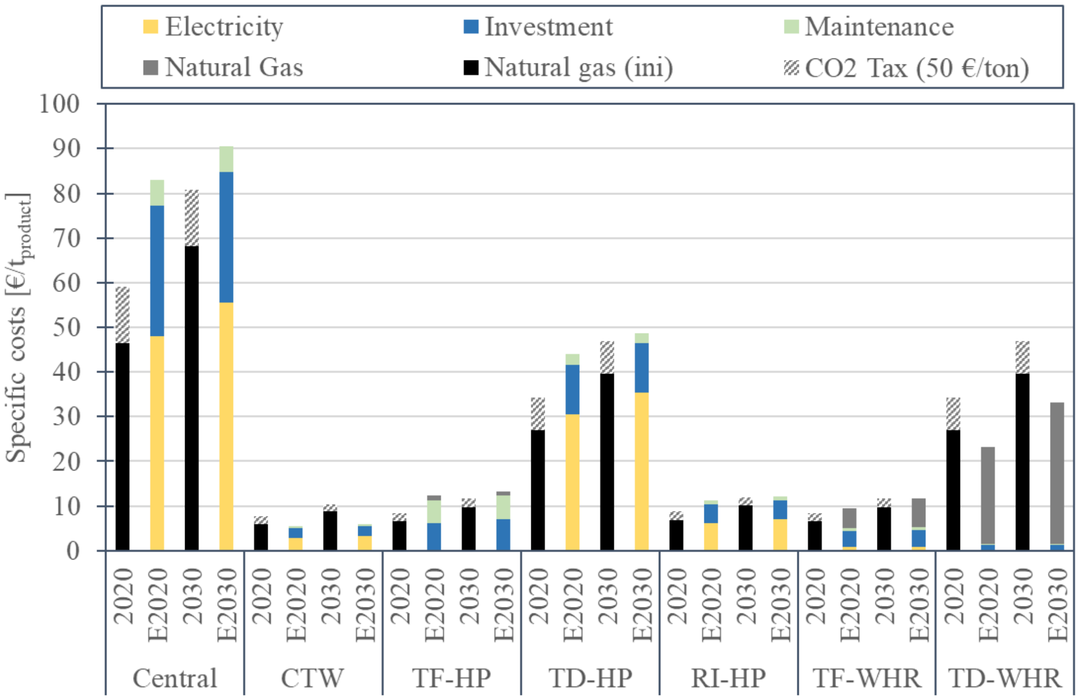


Fig. 12: Specific energy related costs in the years 2020 and 2030 without and with electrification (E) for the different investment opportunities.

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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References

[1] Beyond Zero Emissions, "Zero Carbon Industry Plan: Electrifying Industry," Melbourne, 2018.

[2] A. Gruber, F. Biedermann, and S. von Roon, "Industrielles Power-to-Heat Potenzial," in *9. Internationale Energiewirtschaftstagung an der TU Wien*, 2015, pp. 1–20.

[3] C. Bataille *et al.*, "A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris agreement," *J. Clean. Prod.*, vol. 187, pp. 960–973, 2018.

[4] B. Zühlsdorf, F. Bühler, M. Bantle, and B. Elmegaard, "Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C," *Energy Convers. Manag. X*, vol. 2, no. January, p. 100011, Apr. 2019.

[5] F. Bühler, B. Zühlsdorf, T.-V. Nguyen, and B. Elmegaard, "A comparative assessment of electrification strategies for industrial sites: Case of milk powder production," *Appl. Energy*, vol. 250, pp. 1383–1401, Sep. 2019.

[6] H. Wiertzema, M. Åhman, and S. Harvey, "Bottom-up methodology for assessing electrification options for deep decarbonisation of industrial processes," *Eceee Ind. Summer Study Proc.*, pp. 389–397, 2018.

[7] M. Åhman, L. J. Nilsson, and B. Johansson, "Global climate policy and deep decarbonization of energy-intensive industries," *Clim. Policy*, vol. 17, no. 5, pp. 634–649, 2017.

[8] P. Bobák, M. Pavlas, V. Kšenzuliak, and P. Stehlík, "Analysis of Energy Consumption in Professional Laundry Care Process," vol. 21, pp. 109–114, 2010.

[9] P. Bobák, M. Pavlas, V. Máša, and Z. Jegla, "Heat Recovery in Professional Laundry Care Process," *Chem. Eng. Trans.*, vol. 29, no. 2012, pp. 391–396, 2013.

[10] V. Máša, P. Bobák, P. Kuba, and P. Stehlík, "Analysis of energy efficient and environmentally friendly technologies in professional laundry service," *Clean Technol. Environ. Policy*, vol. 15, no. 3, pp. 445–457, 2013.

[11] P. Kuba, P. Bobák, V. Máša, and M. Vondra, “Acquisition of Operational Data in Industrial Laundry Facilities,” *Chem. Eng. Trans.*, vol. 39, pp. 1645–1650, 2014.

[12] M. R. Conde, “Energy conservation with tumbler drying in laundries,” *Appl. Therm. Eng.*, vol. 17, no. 12, pp. 1163–1172, 1997.

[13] P. Bengtsson, J. Berghel, and R. Renström, “Performance Study of a Closed-Type Heat Pump Tumble Dryer Using a Simulation Model and an Experimental Set-Up,” *Dry. Technol.*, vol. 32, no. 8, pp. 891–901, 2014.

[14] V. Yadav and C. G. Moon, “Modelling and experimentation for the fabric-drying process in domestic dryers,” *Appl. Energy*, vol. 85, no. 2–3, pp. 80–95, 2008.

[15] Carbon Trust, “Industrial Energy Efficiency Accelerator: Guide to the laundries sector executive summary,” no. September, pp. 1–68, 2010.

[16] B. Zühlsdorf, J. K. Jensen, and B. Elmegaard, “Numerical models for the design and analysis of heat pumps with zeotropic mixtures, Rev01” Technical University of Denmark, Copenhagen, p. https://figshare.com/s/575b3a3760275aee119e, 2018.

[17] A. Meroni, B. Zühlsdorf, B. Elmegaard, and F. Haglind, “Design of centrifugal compressors for heat pump systems,” *Appl. Energy*, vol. 232, pp. 139–156, Dec. 2018.

[18] B. Zühlsdorf, C. Schlemminger, M. Bantle, K. Evenmo, and B. Elmegaard, “Design Recommendations for R718 Heat Pumps in High Temperature Applications,” in *Proceedings of 13th IIR Gustav Lorentzen Conference on Natural Refrigerants*, 2018.

[19] R. Turton, R. C. Bailie, W. B. Whiting, J. A. Shaeiwitz, and D. Bhattacharyya, *Analysis, Synthesis, and Design of Chemical Processes*, Fourth. Pearson Education, Inc., 2009.

[20] G. D. Ulrich and P. T. Vasudevan, *Chemical Engineering Process Design and Economics: A Practical Guide*, Second. Durham, New Hampshire: Process Publishing Company, 2004.

[21] T. S. Ommen *et al.*, “Technical and Economic Working Domains of Industrial Heat Pumps : Part 1 - Vapour Compression Heat Pumps,” *Int. J. Refrig.*, vol. 55, no. 1997, pp. 1–8, 2014.

[22] Danish Energy Agency, “Baseline projection 2018 [In Danish: Basisfremskrivning 2018],” 2018.

[23] PricewaterhouseCoopers, “Overview for the accounting and reimbursement of taxes 2019 [In Danish: Samlet overblik over afregning og godtgørelse af afgifter 2019],” Hellerup, 2018.

[24] M. Schlesinger *et al.*, “Development of energy markets - Energy reference forecast [In German: Entwicklung der Energiemärkte – Energiereferenzprognose],” Basel/Köln/Osnabrück, 2014.

[25] F. Alborzi, A. Schmitz, and R. Stamminger, “Long wash cycle duration as a potential for saving energy in laundry washing,” *Energy Effic.*, vol. 10, no. 4, pp. 823–838, 2017.

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

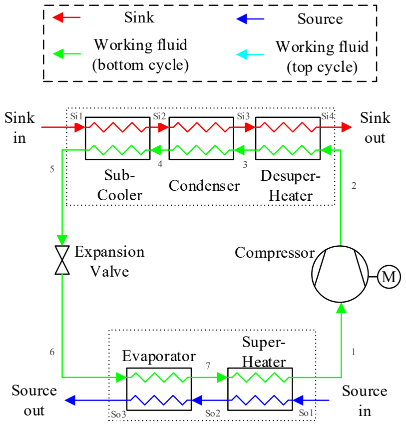
(for each case study:)

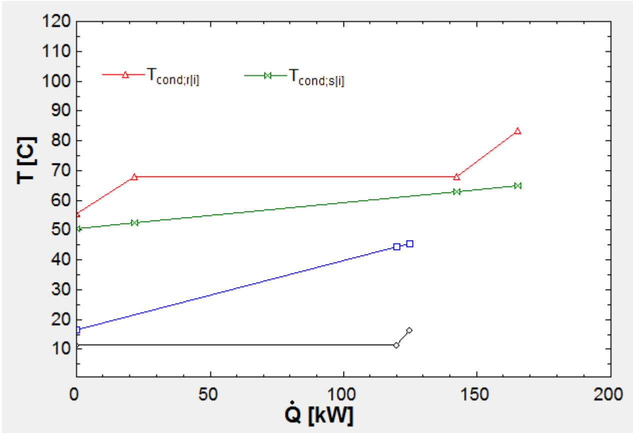
- Case Description
- Electrification Scenarios
- Energy analysis
- Economic analysis

Method
Overall Approach

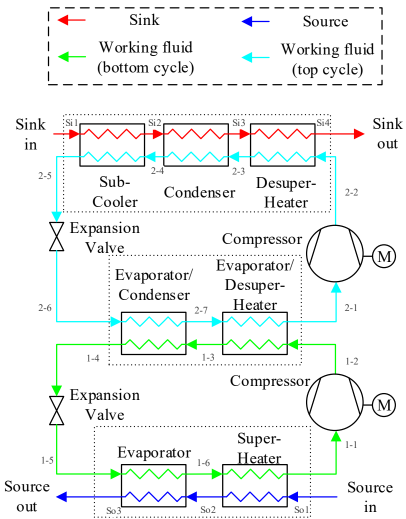
- Data collection and energy mapping
- Thermodynamic models of existing system
- Energy (and exergy) analysis
- Energy optimization (waste heat recovery and process integration)
- Electrification
  - Heat Pump integration
  - Central electrification
- Economic analysis
- Sensitivity analysis

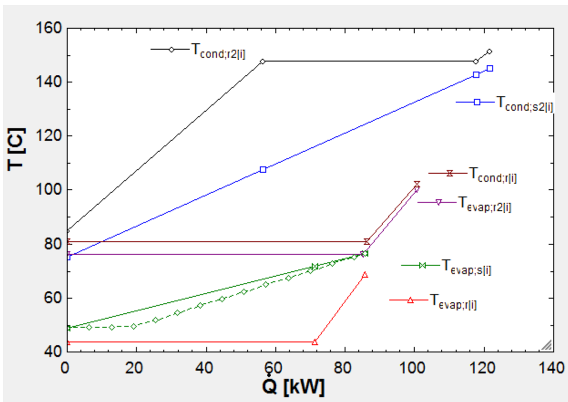
Continuous Tunnel Washer
Single Stage Heat Pump



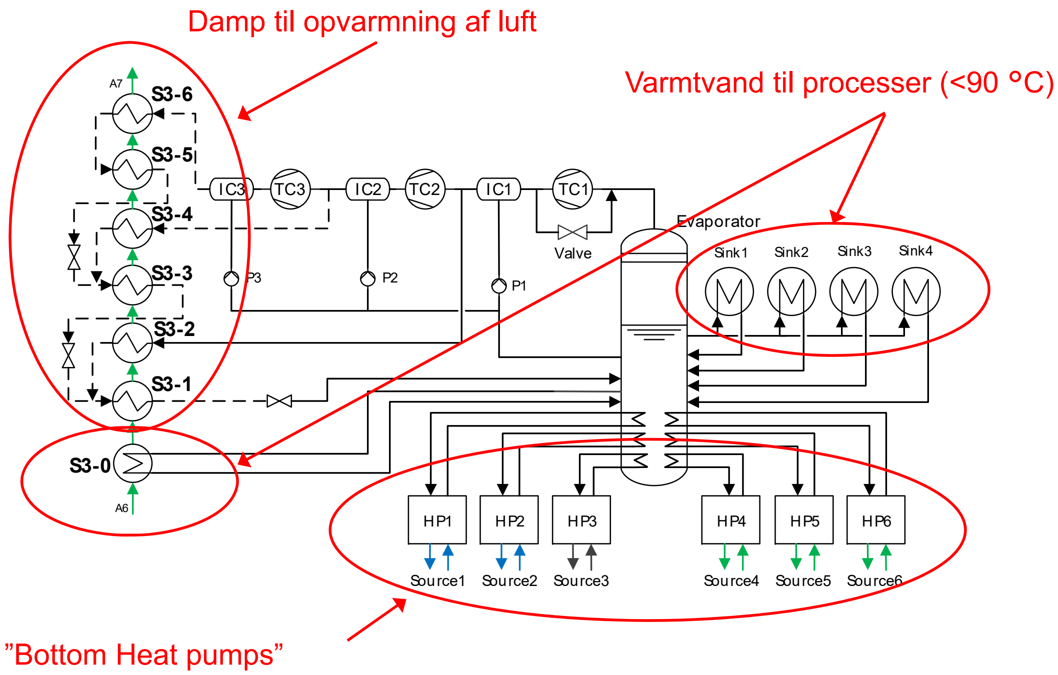


Method
Two Stage Heat Pump



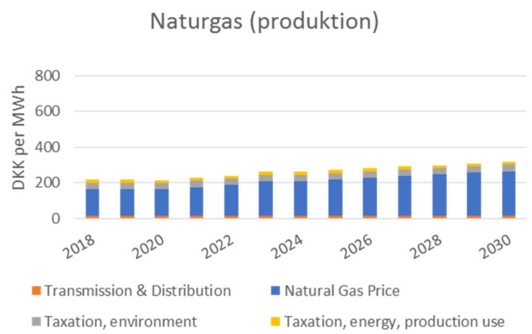


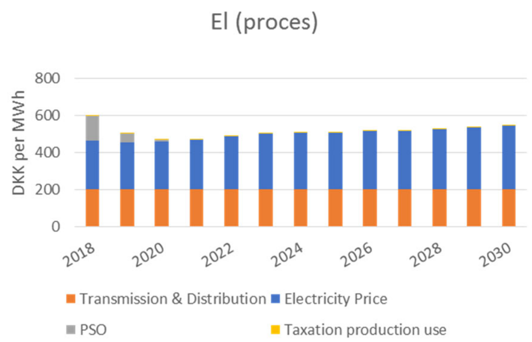
Method
Central Varmepumpe



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 %

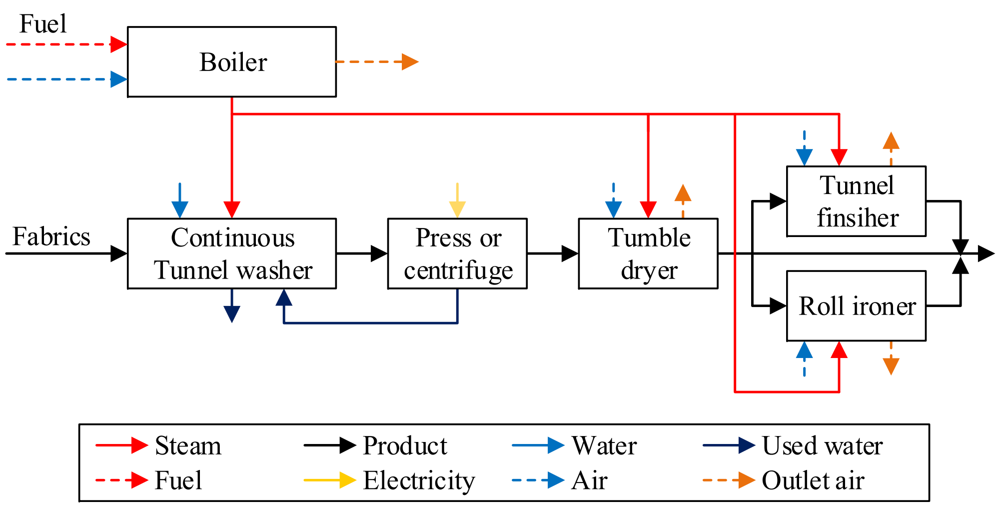




Laundry Case Study

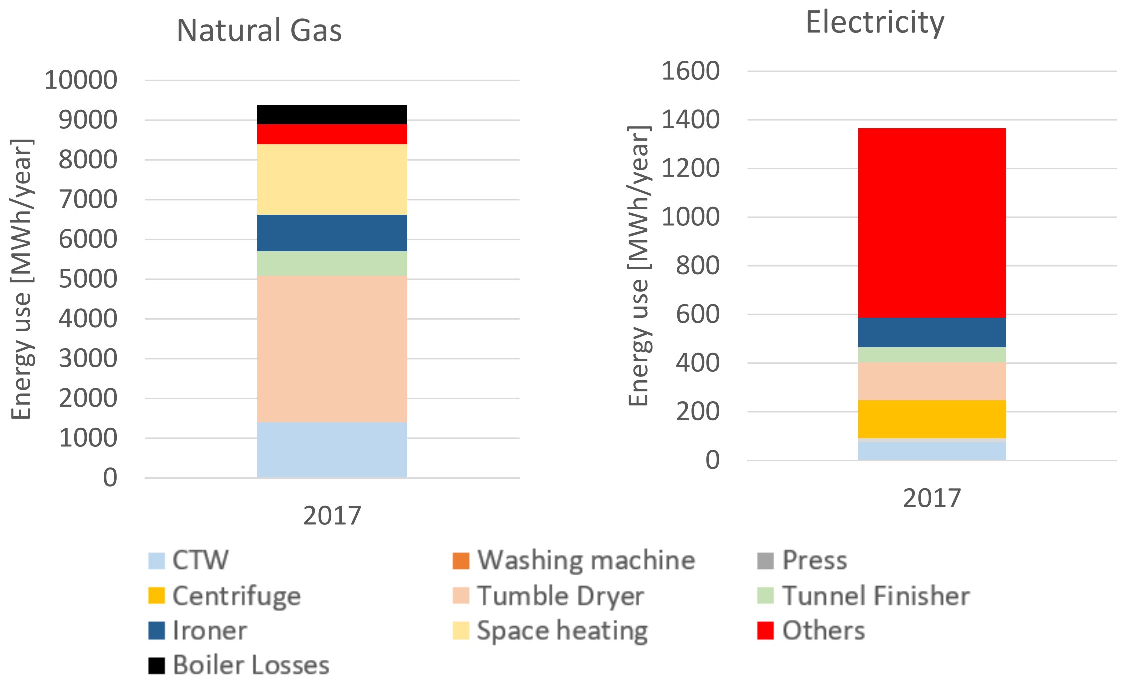
De Forenede Dampvaskerier (DFD)

Overall system diagram

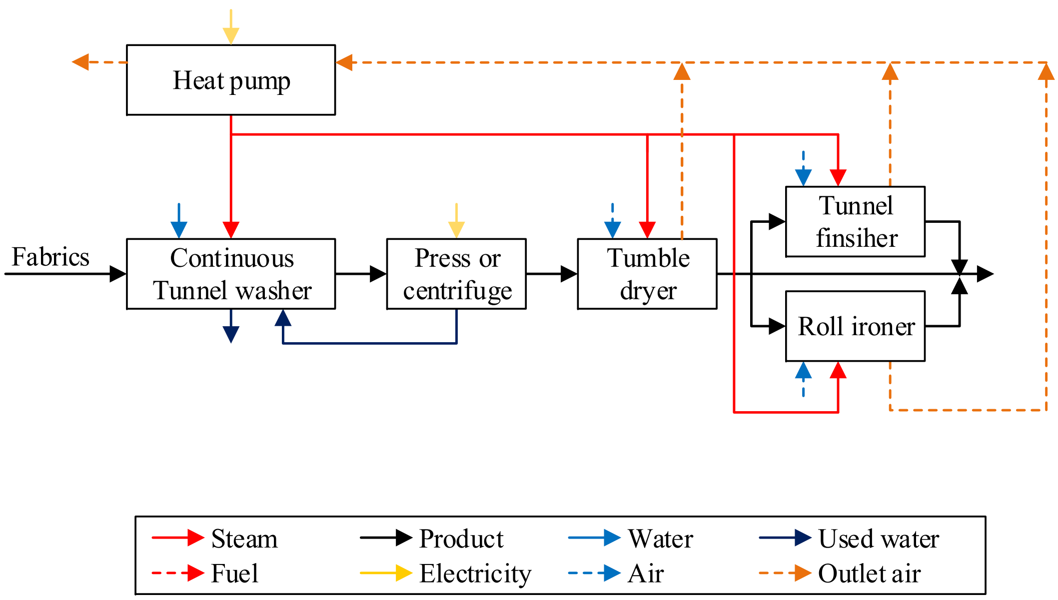


- Central utility boiler (8.2 MW @ 180°C/ 9 bar)

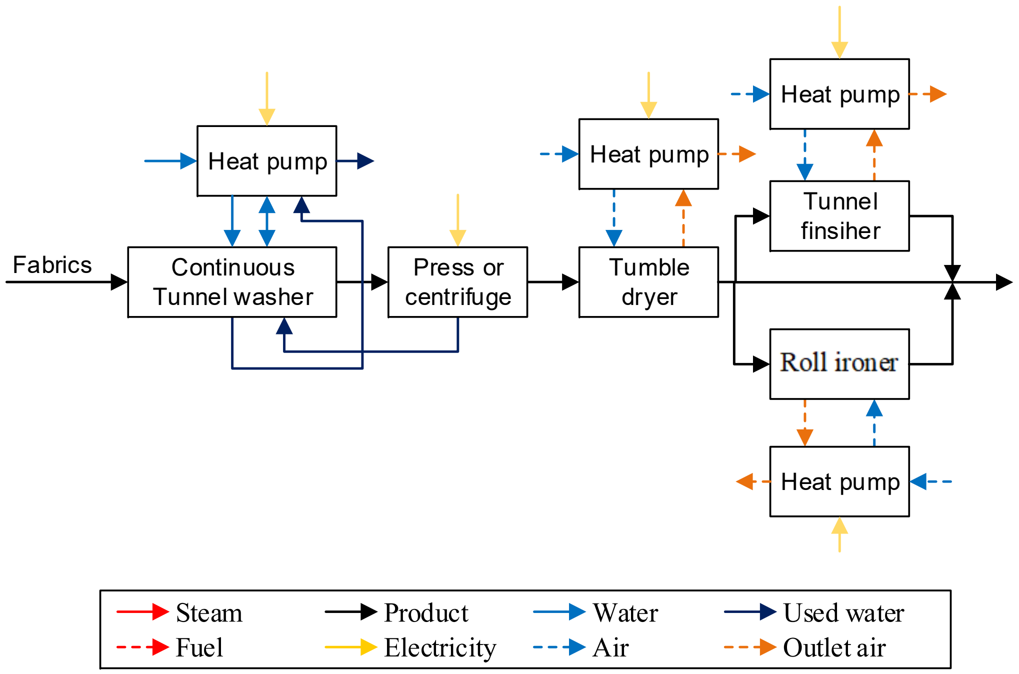
Laundry case study
Energy balance



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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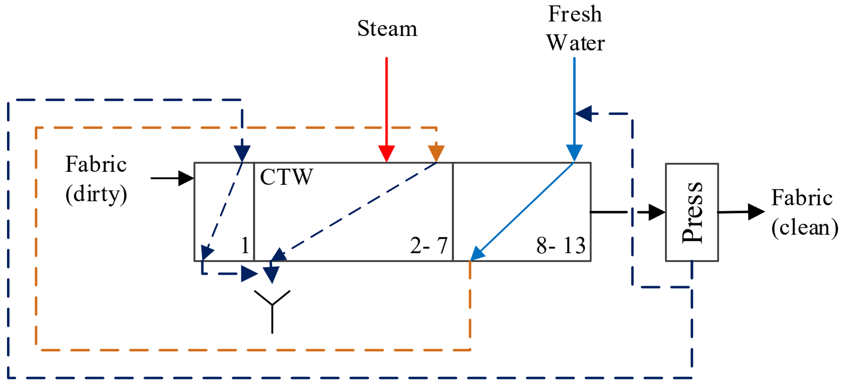
Continuous Tunnel Washer
Simplified View

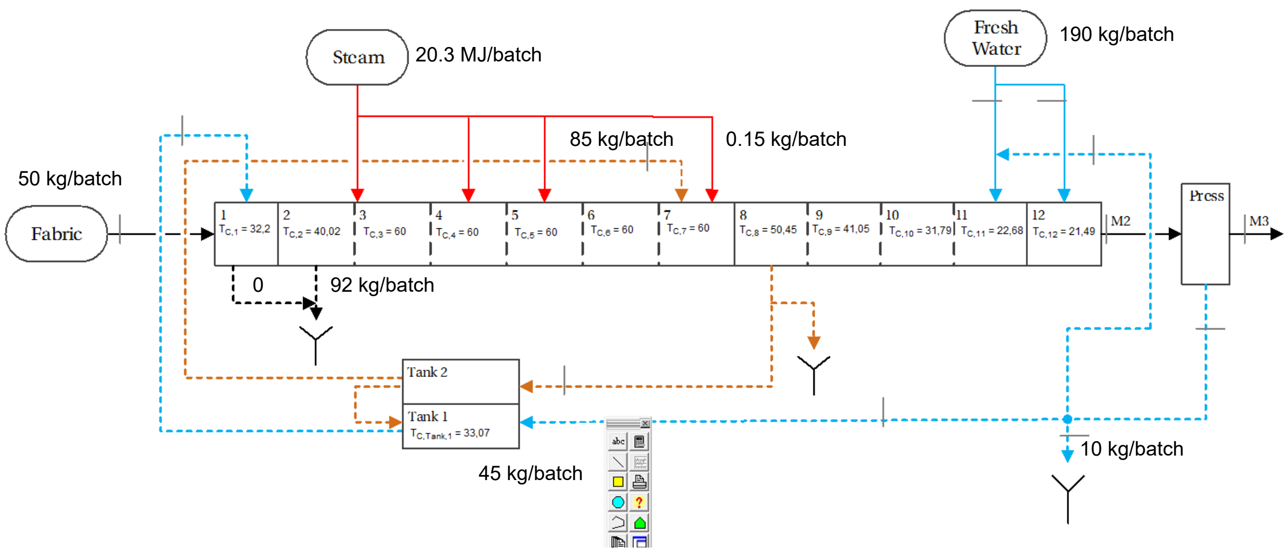


Continuous Tunnel Washer
Model

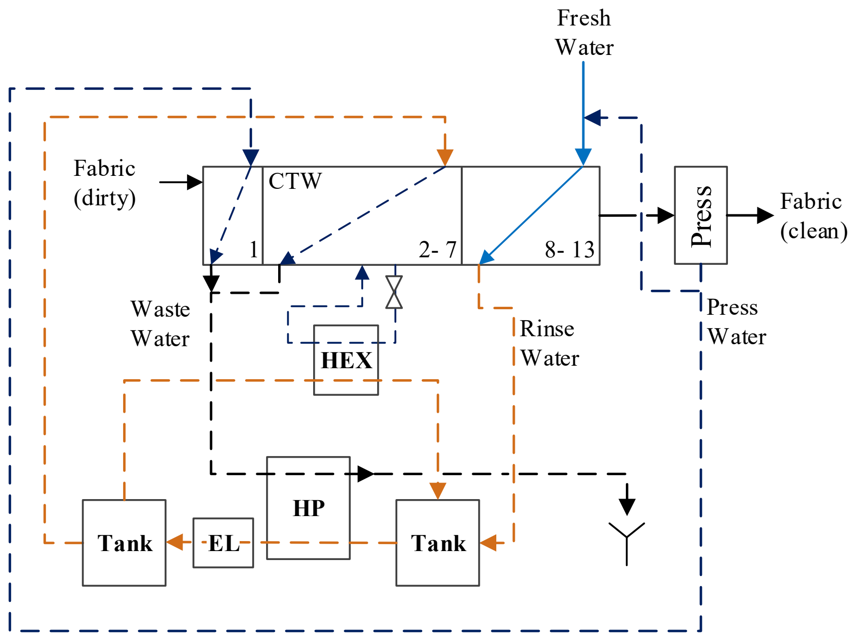
- Cycle time 150 s
- Batch size 50 kg
- No heat losses

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

- Optimized CTW
- Countercurrent operation



Continuous Tunnel Washer
Electrification and Waste heat recovery - Concept



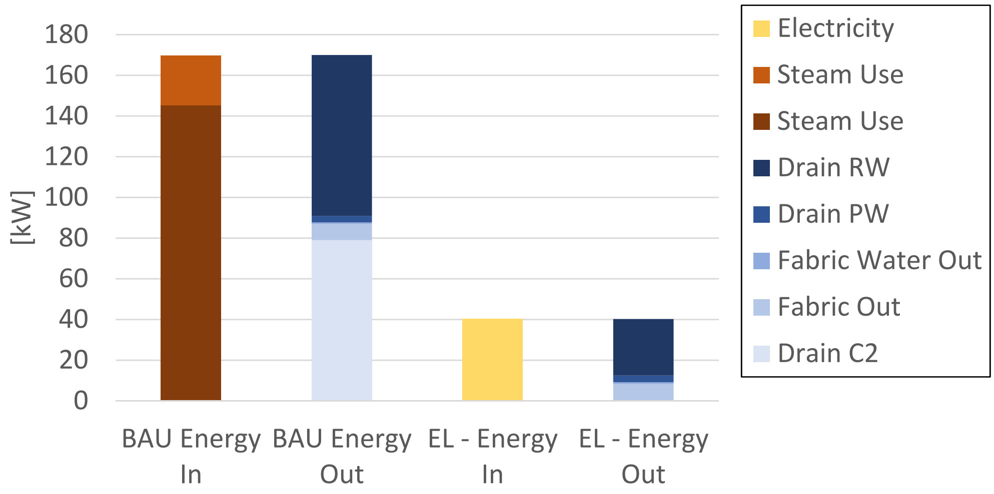
Continuous Tunnel Washer
HP – Modelling & Results

- 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})

Tunnel washer
Results – Energy analysis



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

Tunnel finisher
Working principle

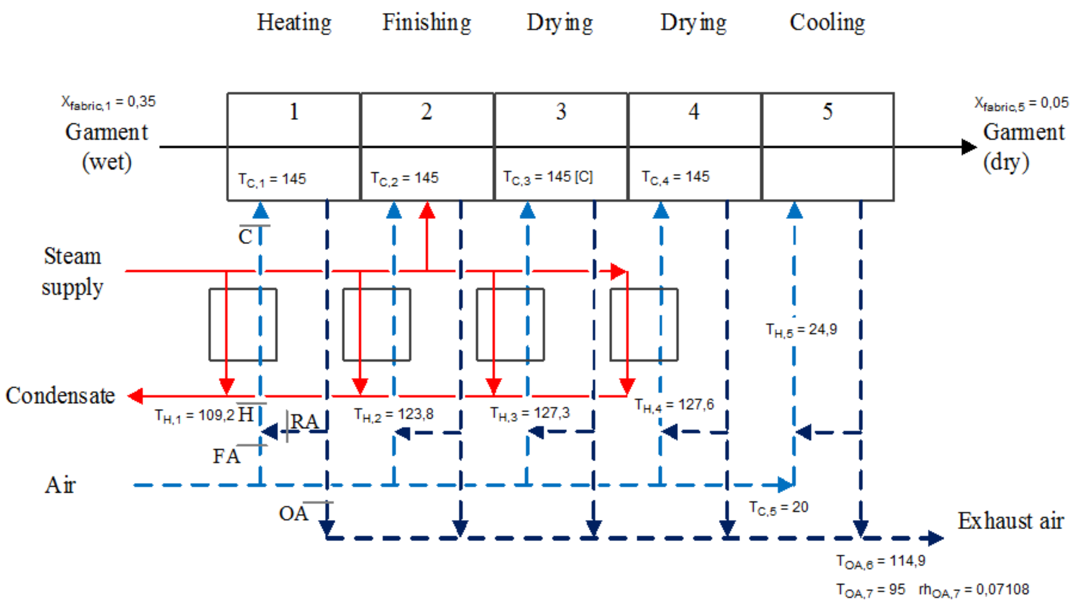
Working Principle

- 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

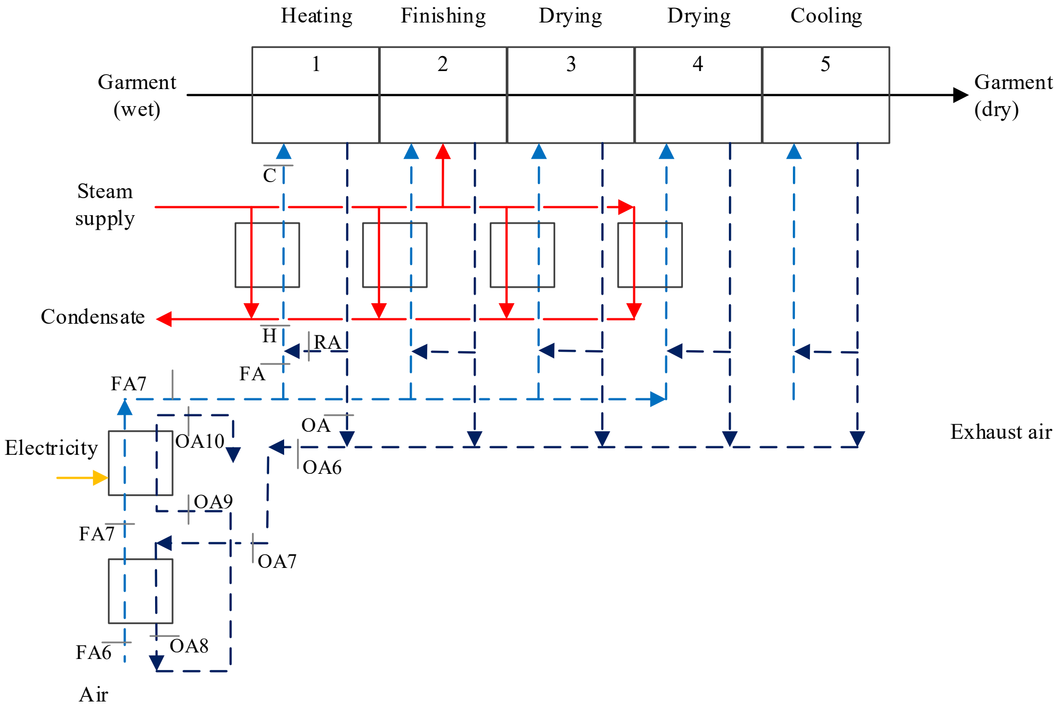
Assumptions

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

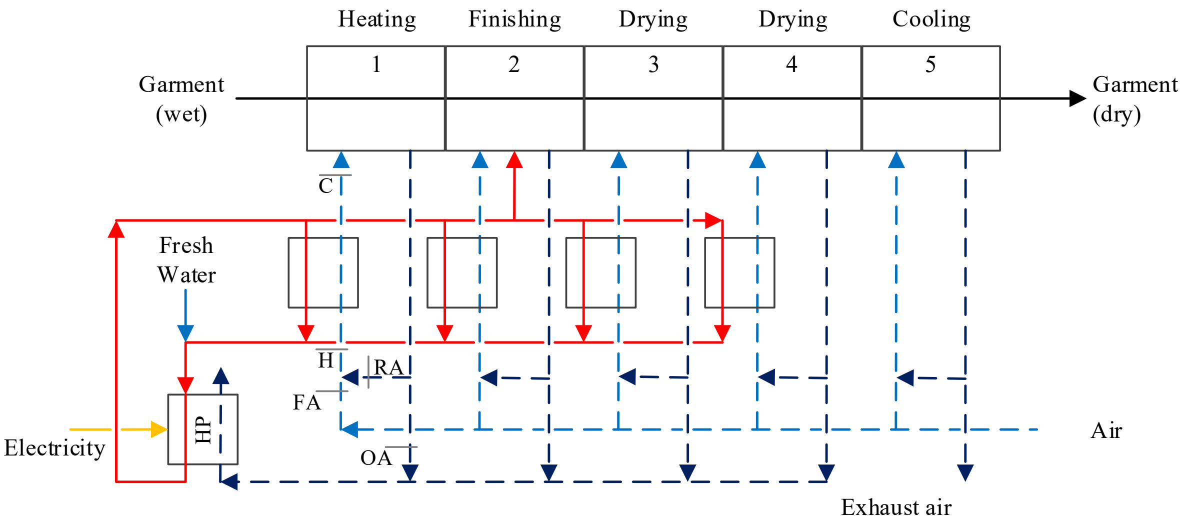
Tunnel finisher
Model



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

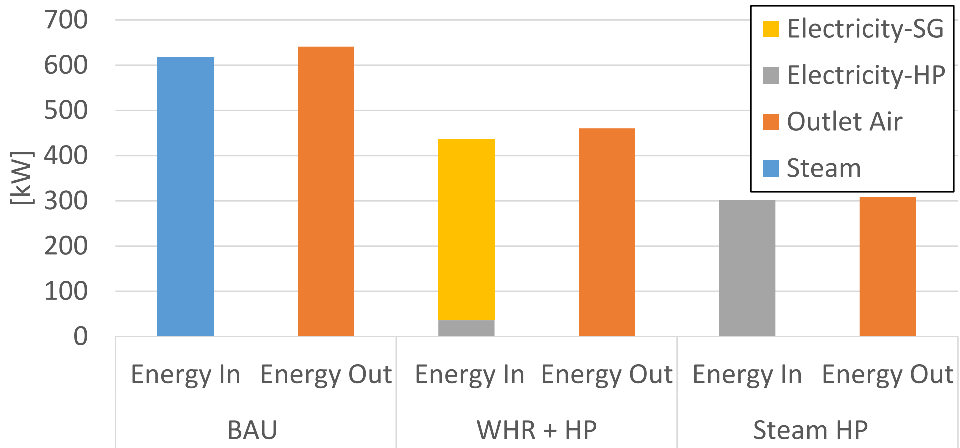
- COP theoretical: $COP_L = 6.3$
- COP model (two stage): COP = 1.94

} 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})

DTU

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

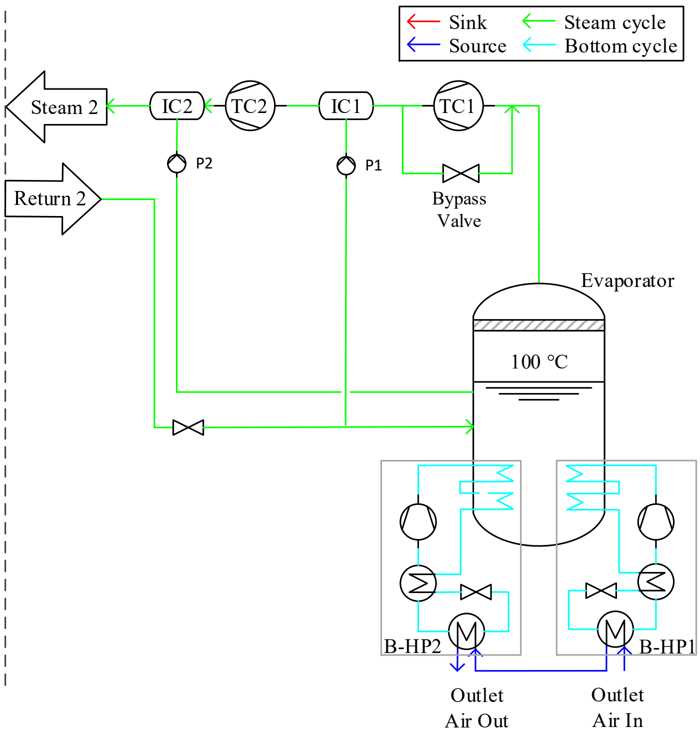
DTU

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

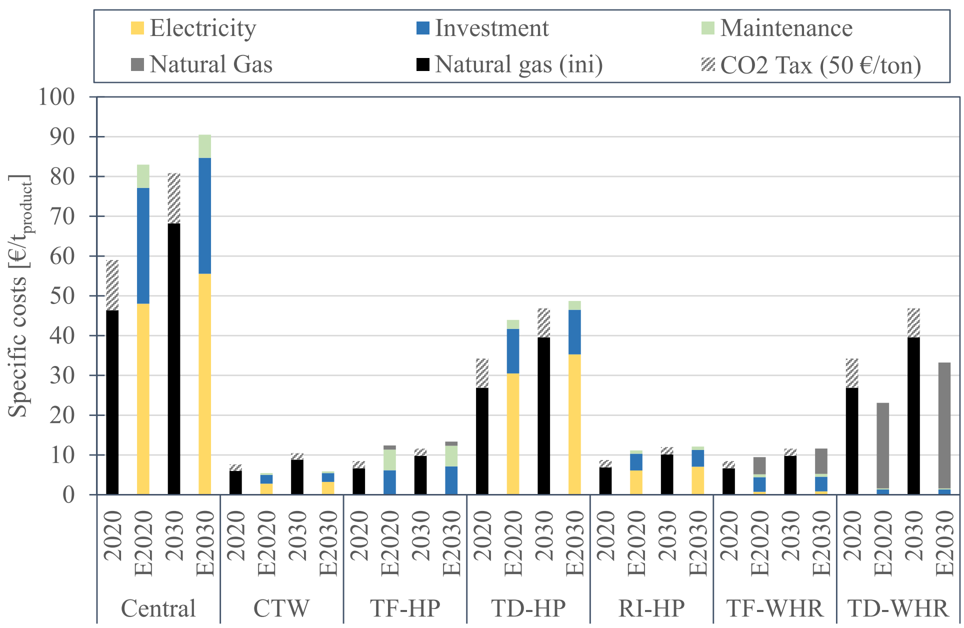
		Total Investment [€]	Specific Investment [€/kW$_{elect}$]
Utility	Central Steam HP	2,357,343	2,216
CTW	WHR + HP	180,599	786
Tunnel Finisher	Steam HP	422,285	2,454
Tubmble Dryer	Steam HP	912,428	1,671
Roll Ironer	Steam HP	343,186	1,856
Tunnel Finisher	WHR + HP	299,459	3,025
Tubmble Dryer	WHR	107,277	394

Central Electrification (Utility row)

1.858.000 € – De-central Electrification (CTW, Tunnel Finisher Steam HP, Tubmble Dryer Steam HP, Roll Ironer rows)

Energy Efficiency (Tunnel Finisher WHR + HP, Tubmble Dryer WHR rows)

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!

Fabian Bühler

Danish Energy Agency

FNBR@ens.dk

+45 22471020

Benjamin Zühlsdorf

Technological Institute

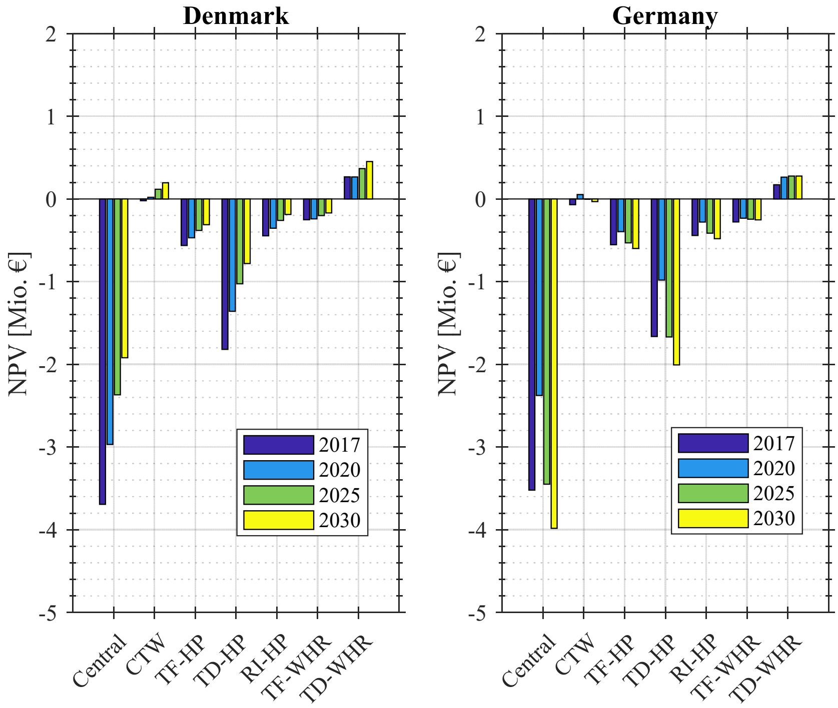
BEZ@teknologisk.dk

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

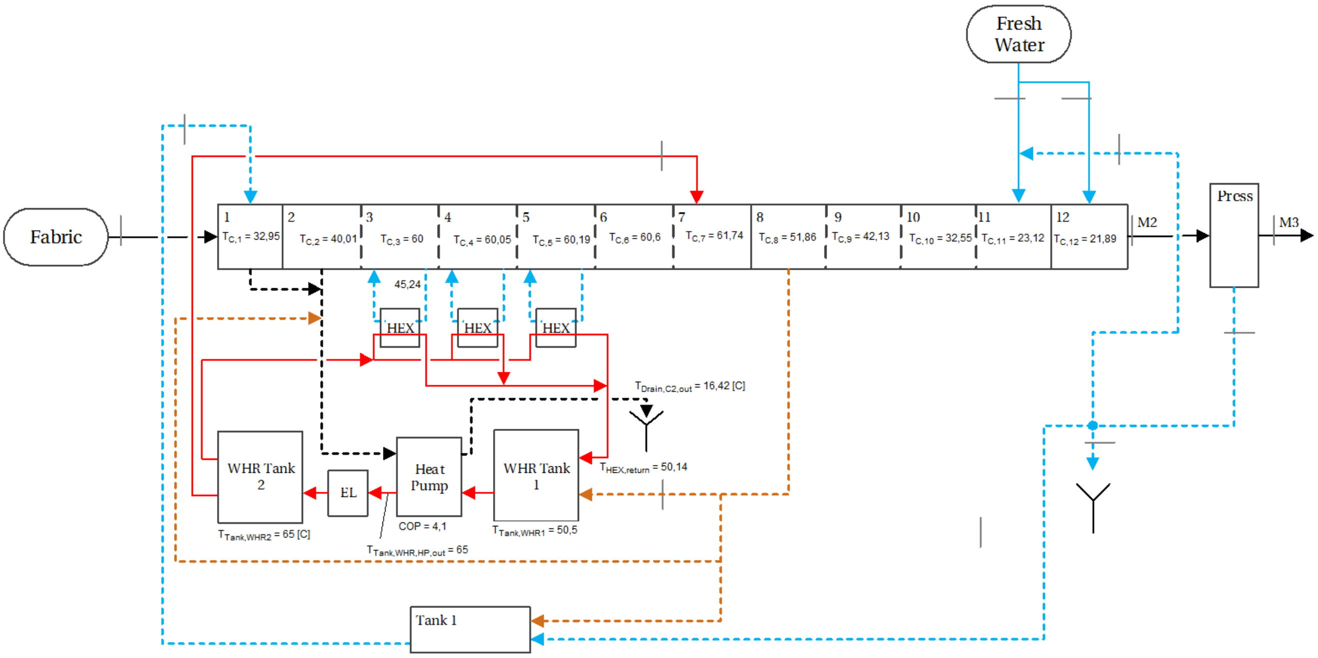
With subsidy similar to the Energy Saving Obligation Scheme (0.05 €/kWh):

			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

DTU

Continuous Tunnel Washer

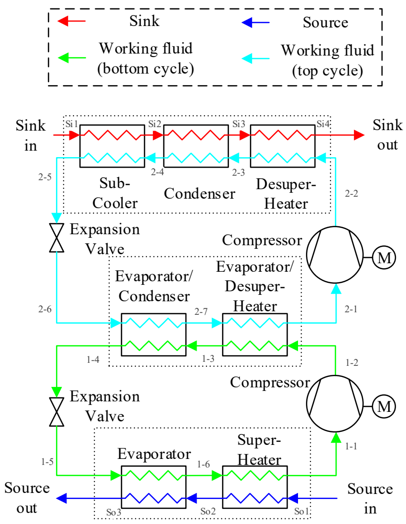
Electrification and WHR – Model results

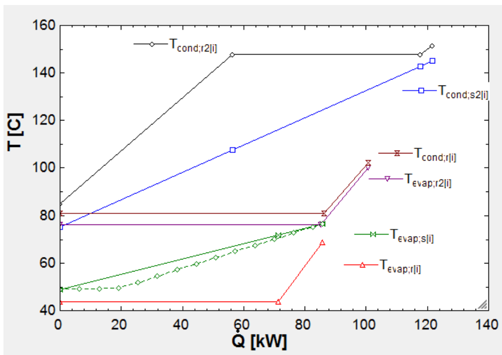


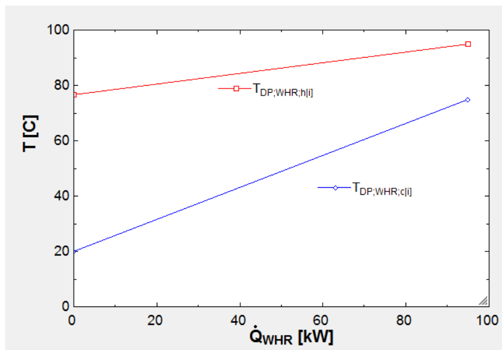
DTU

Tunnel finisher

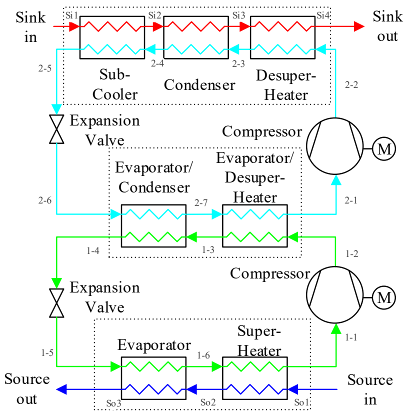
Results - Electrification Option 1

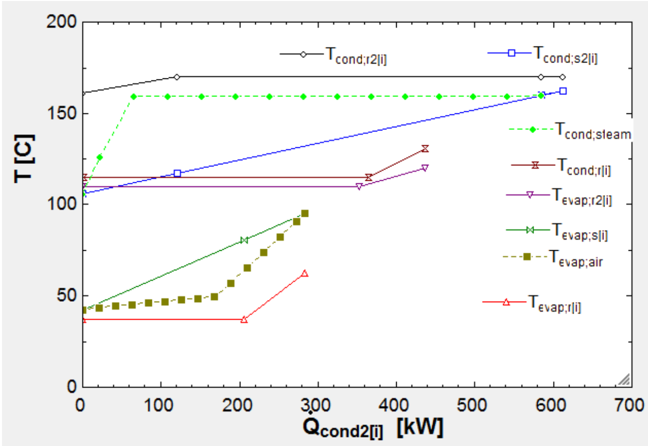






Tunnel finisher
Results - Electrification Option 2



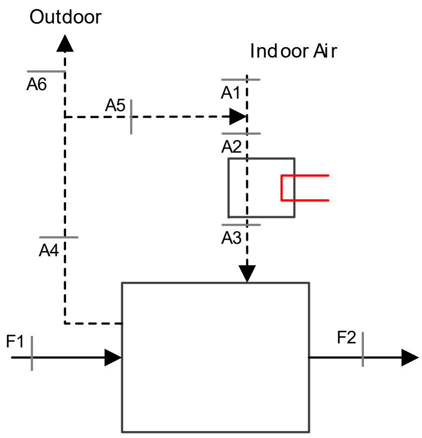


- COP theoretical: $COP_L = 6.3$
- COP model (two stage): $COP = 1.94$

} HP efficiency 31.0 %

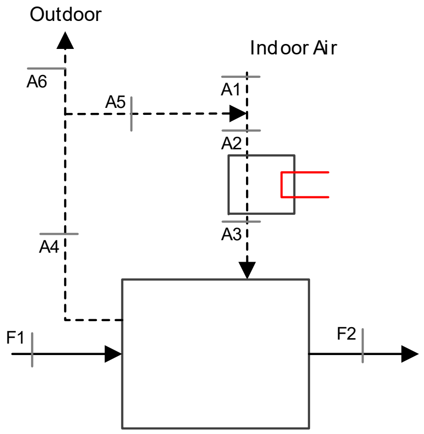
- HP Electricity use: 302 kW (32.7 kWh/100 kg_{fabric})
- Initial energy use: 617.3 kW (66.8 kWh/100 kg_{fabric})

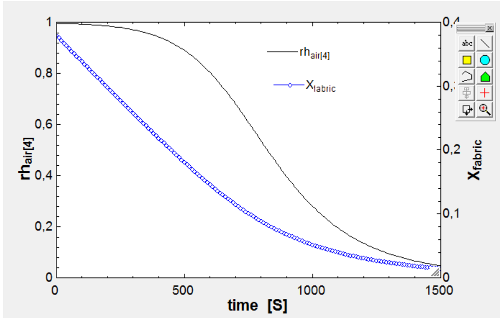
Tumble dryer
Introduction

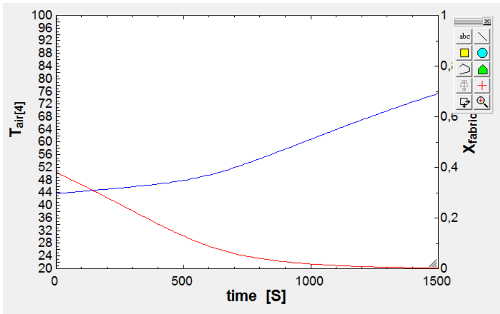


- Challenges
  – Many different dryer operating modes
  – Some literature parameters in model
  – A3 between 90°C and 180°C
- Electrification
  – WHR and HP integration directly in dryer
- Assumptions model
  – Fixed air circulation: 40 %
  – No heat losses
  – No part load considered (WHR)
- Assumptions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

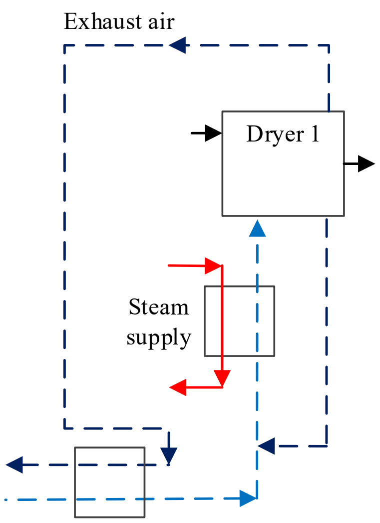
Tumble dryer
Modelling

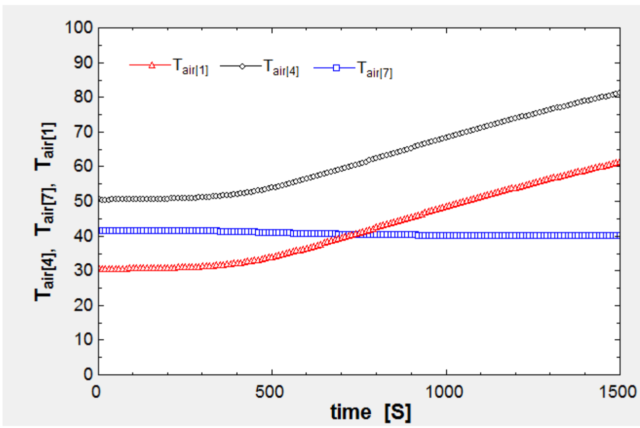






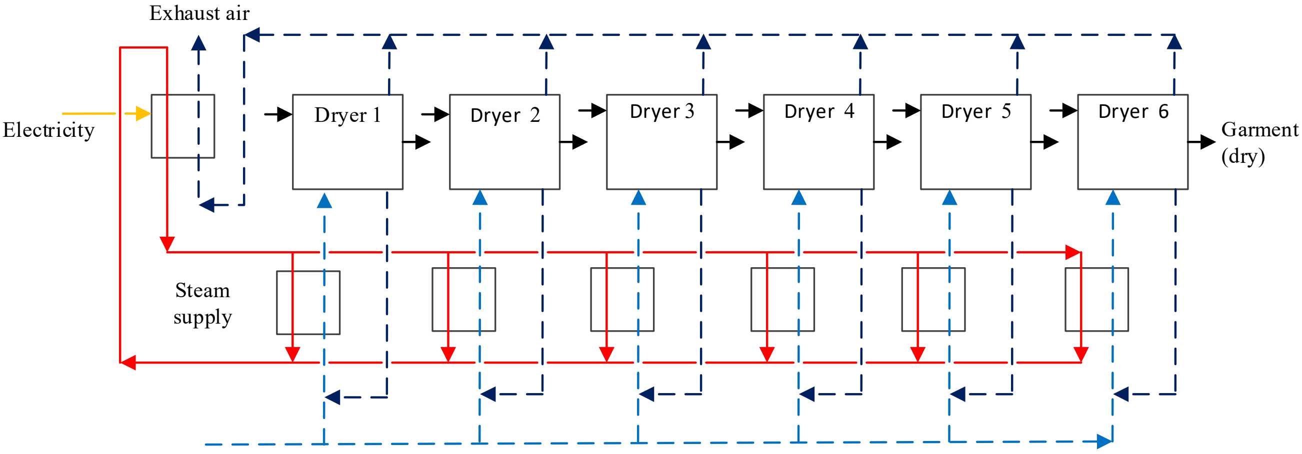
Tumble dryer
Waste heat recovery – Direct heat exchange





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

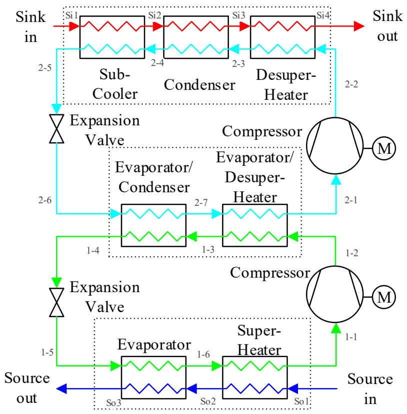
Tumble dryer
Modelling – Electrification

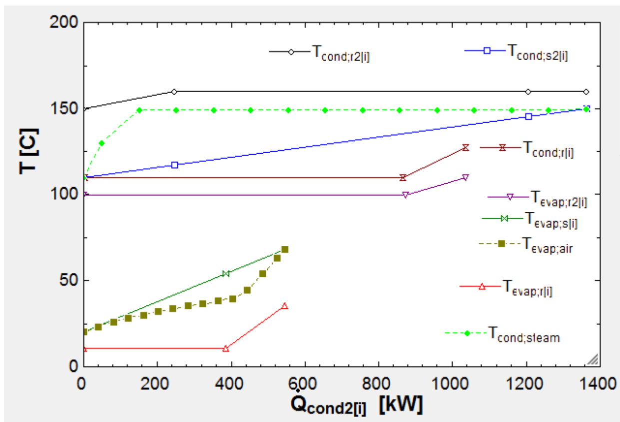


Assumptions

- 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): $COP = 1.67$

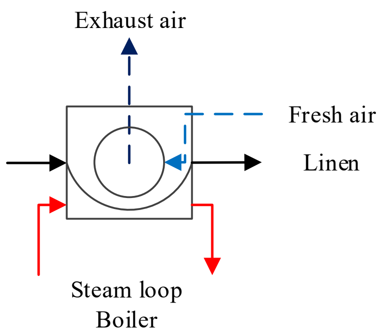
} HP efficiency 38.0 %

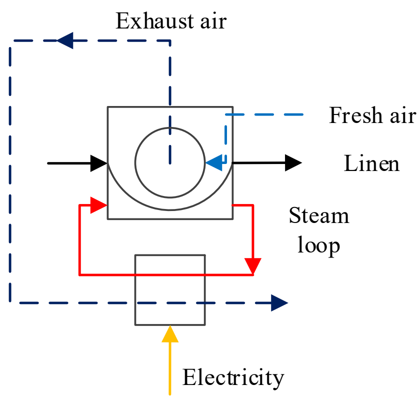
- HP Electricity use: 817 kW ($0.345\ kWh/kg_{fabric}$)
- Initial energy use: 1363 kW ($0.609\ kWh/kg_{fabric}$)

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



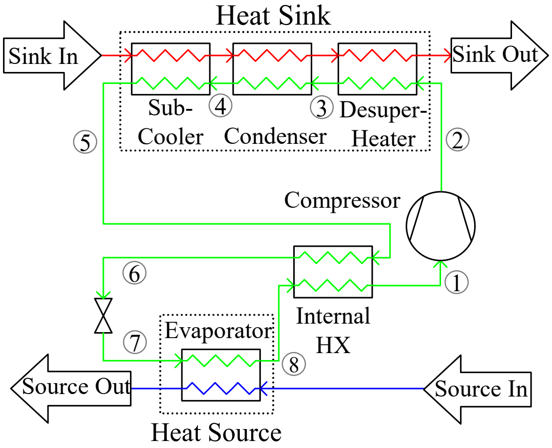


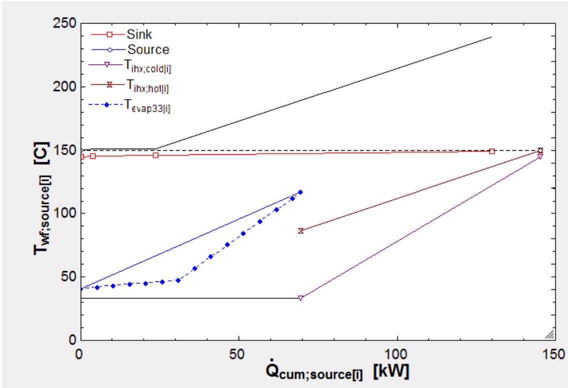
Capacity	275 kg/h
Remaining humidity	36 %
Air inflow	1500 kg/h
Air outflow	1500 kg/h
Hum air out	0.0738 kg/kg
T air out	117 C
T air in	24 C
Energy use	130 kW
Steam use	205 kg/h

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

DTU

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})

DTU

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

Nasrin Arjomand Kermani[a], Morten Sandstrøm Petersen[b], Niklas Bagge Mogensen[b], Fabian Bühler[a], Brian Elmegaard[a], Fridolin Müller Holm[b]

[a]*Themal Energy Section, Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, Bygning 403, 2800 Kgs. Lyngby, Denmark*

[b]*Viegand Maagøe A/S, Nørre Farimagsgade 37, 1364 København K, Denmark*

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.

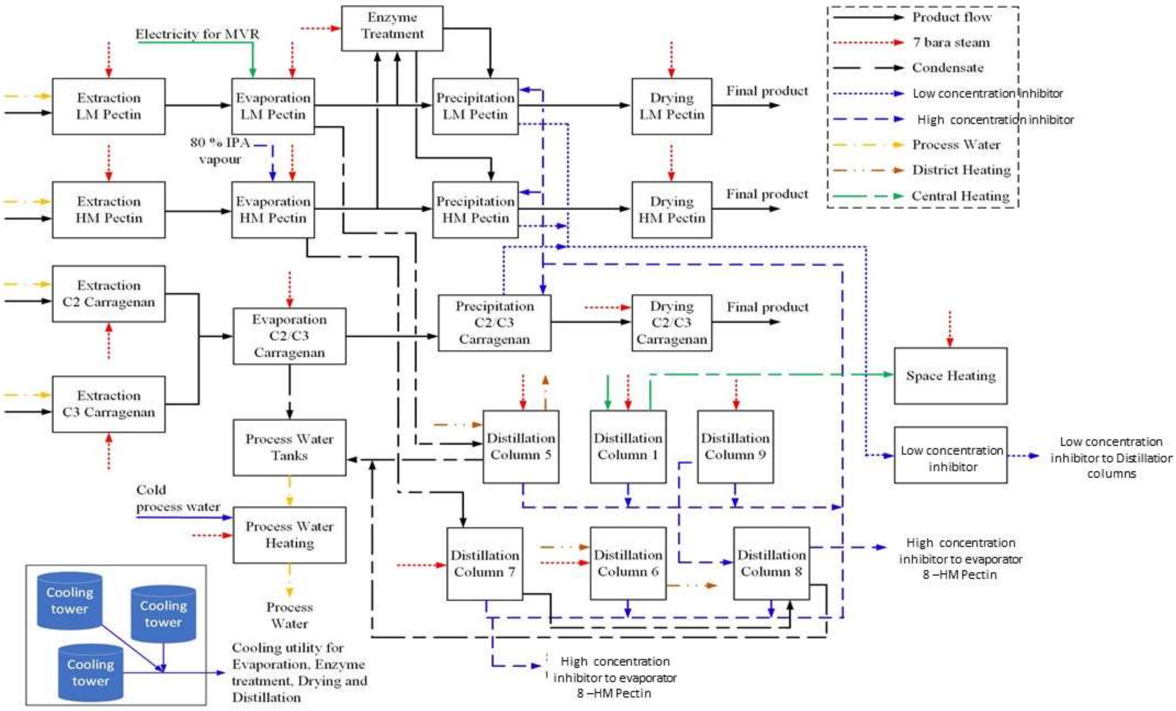


Figure-1: Product flow and utility chart for processes at CP Kelco without Locust Bean Gum production.

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.

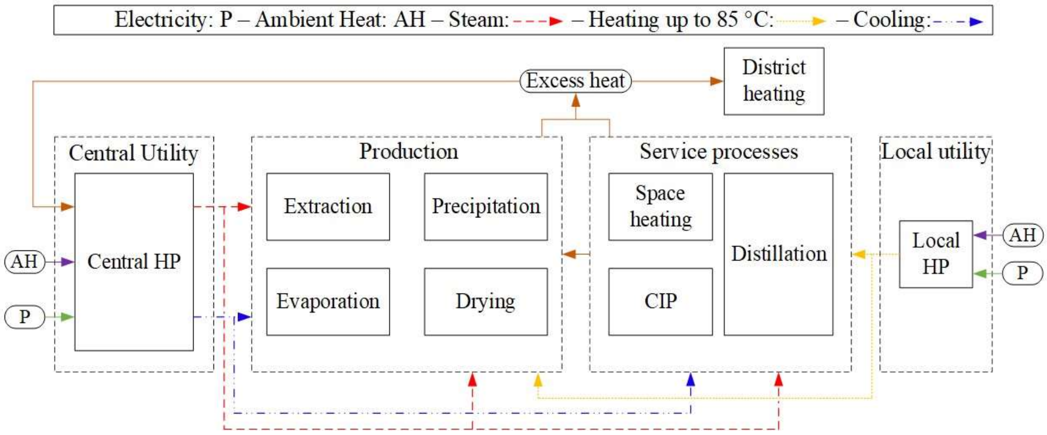


Figure 2- Case A with central steam generation heat pump and local heat pumps.

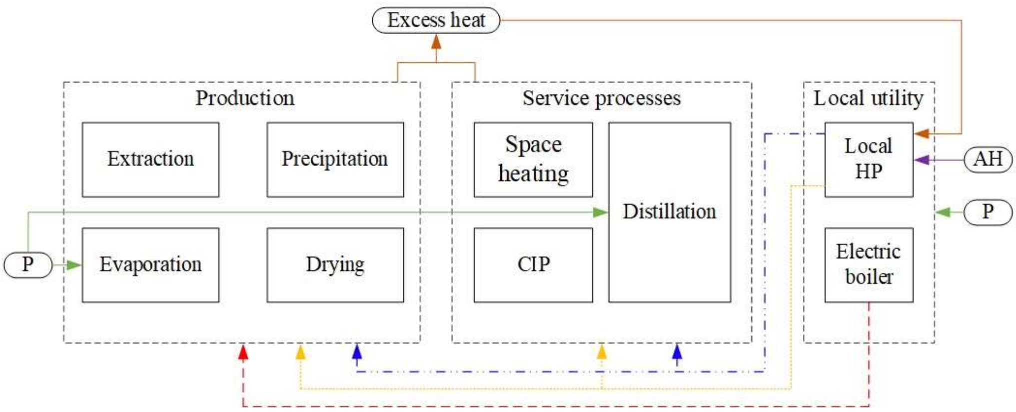


Figure-3: Case C with local heat pumps, local electric boilers and MVR on evaporation and distillation sections.

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.

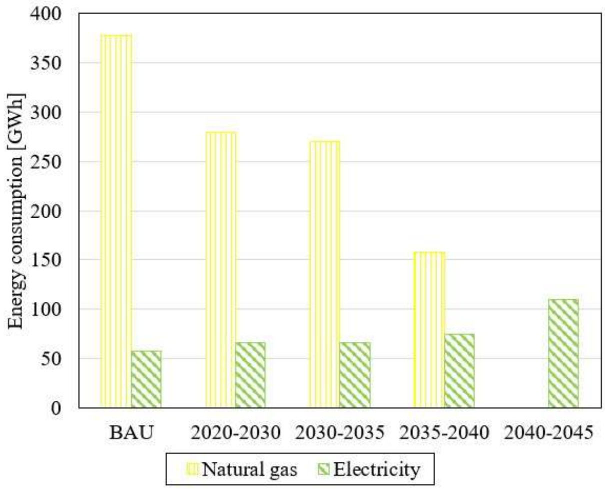


Figure-1: Development of energy use from BAU to full electrification in case C, at CP Kelco

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.

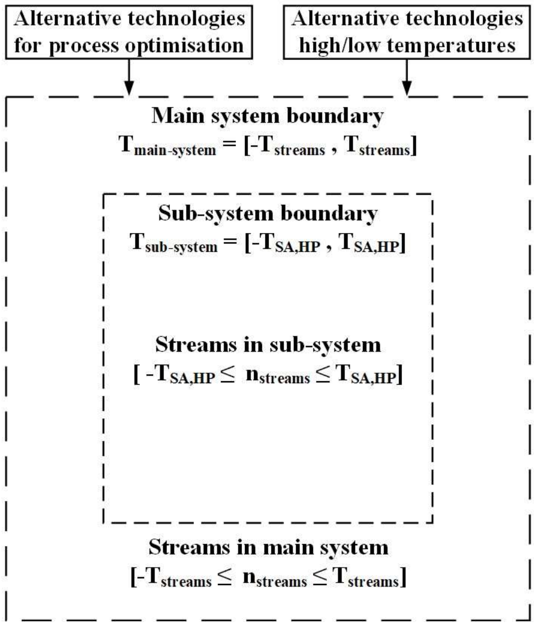


Figure-2: System boundaries of electrification strategy including sub-system boundaries for state-of-the-art heat pump temperature limitations

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.

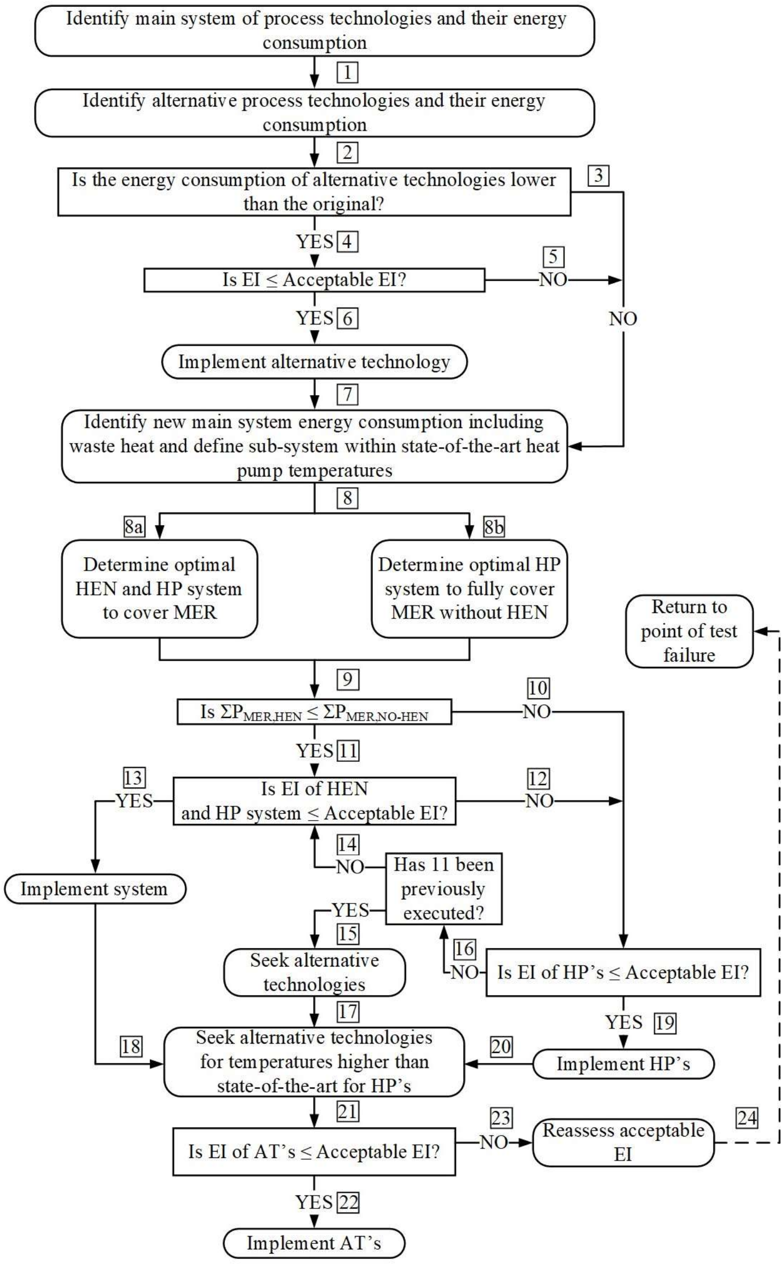


Figure-3: Suggestion for general electrification approach for low-to-medium temperature processes in production industries.

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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Bibliography

[1] M. S. Petersen, N. B. Mogensen,"Electrification of industrial processes with low-to-medium temperature heat demand: case study of pectin production", Master Thesis, Department of Mechanical Engineering, Technical University of Denmark, 2020.

[2] Danish Energy Agency. *Standard heating value and CO2-emissions - reporting of CO2-emissions for 2017 (Danish:Standardfaktorer for brændværdier og CO2-emissioner - indberetning af CO2-udledning for 2017)*. Memorandum. 2018.

[3] P. Capros, A. De Vita, and N. Tasios. *EU Reference Scenario 2016 - Energy, transport and GHG emissions Trends to 2050*. Report. 2016.

Viegand Maagøe

Welcome

Electrification at CP Kelco

Viegand Maagøe

Background

Experience from the industry

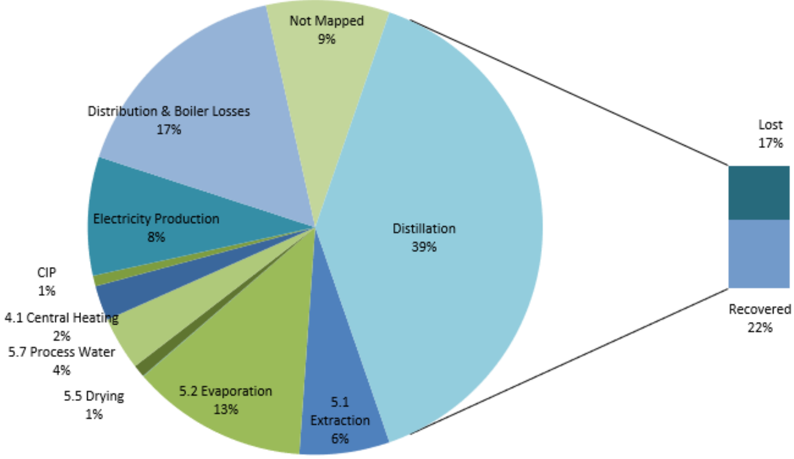
- CP Kelco in Lille Skensved is owned by J. M. Huber Corporation
- A traditional manufacturing site
- Pectin and Carrageenan production from citrus peels and seaweed
- Wide span of processes such as extraction, evaporation, precipitation, and distillation
- CP Kelco is a large consumer of primary energy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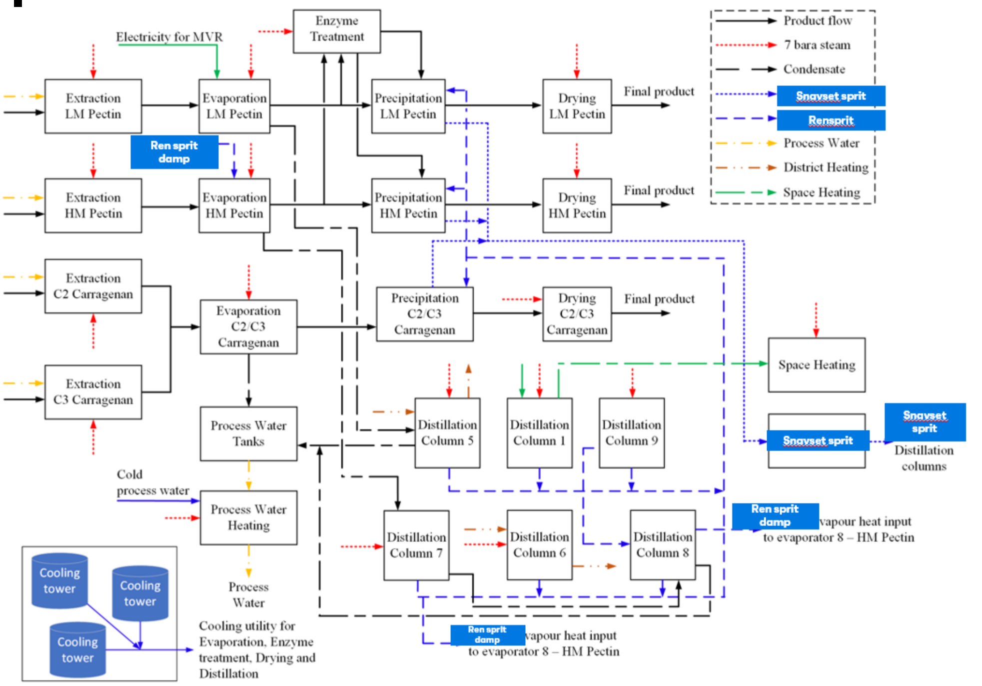
A highly integrated process

Experience from the industry

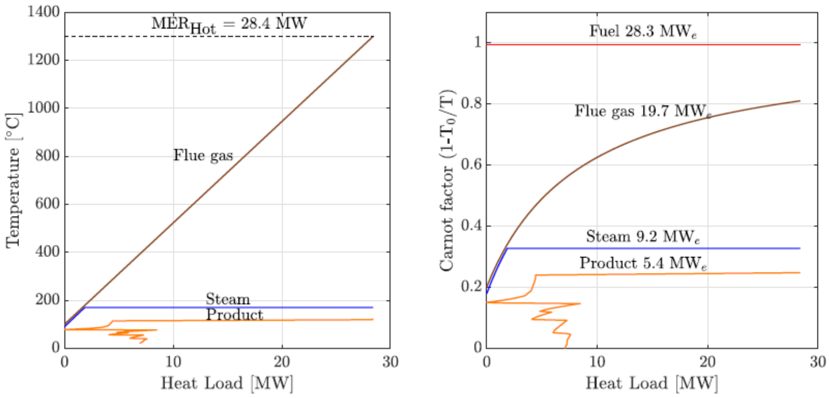
1. Manufacturing processes
   - Extraction
   - Evaporation
   - Enzyme treatment
   - Precipitation
   - Drying
2. Service processes
   - Distillation
   - Process water heating
   - Space heating
   - CIP (Cleaning In Place)
3. Thermal utility for processes
   - Steam
   - Cooling towers



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

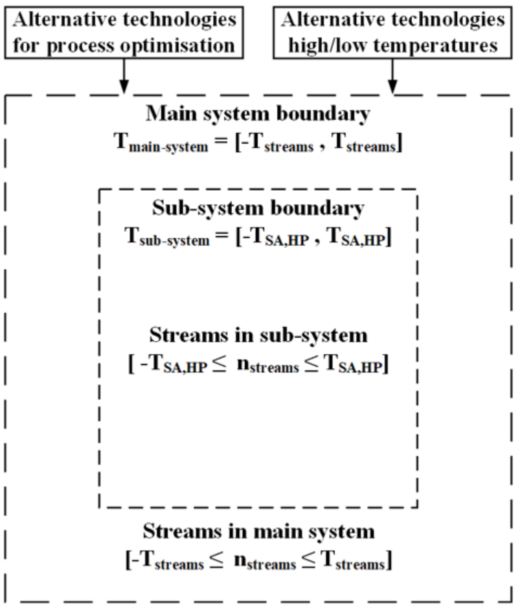


(a) Energy basis (b) Exergy basis

Electrification method

Experience from the industry

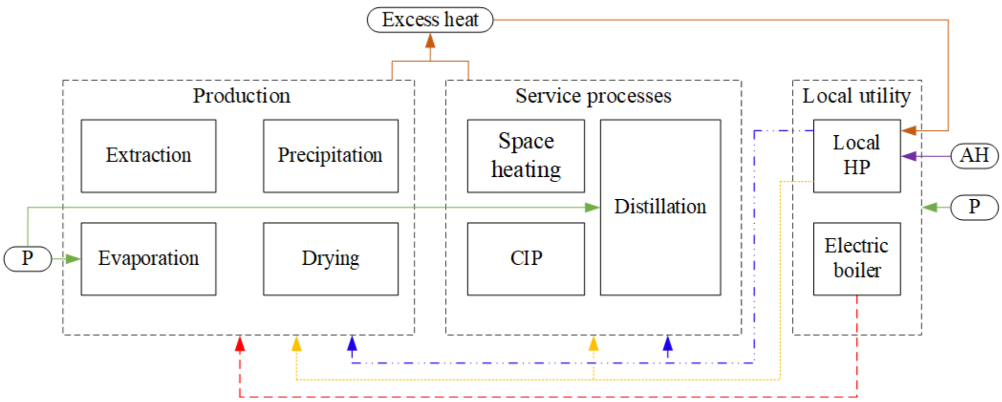
- Main system – and sub-system boundaries
- Process integration before electrification should not necessarily be prioritized
- Alternative technologies should be investigated for the entire site
- Remaining product streams are analyzed for state-of-the-art potential of heat pumps in various scenarios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

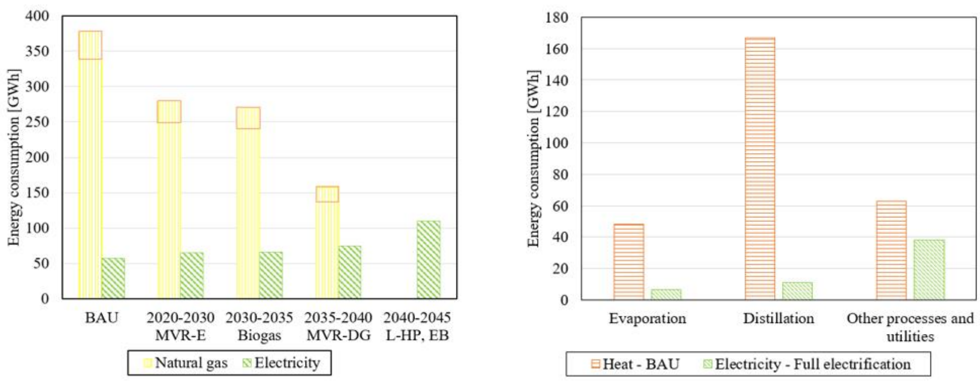


Potentials found from electrification

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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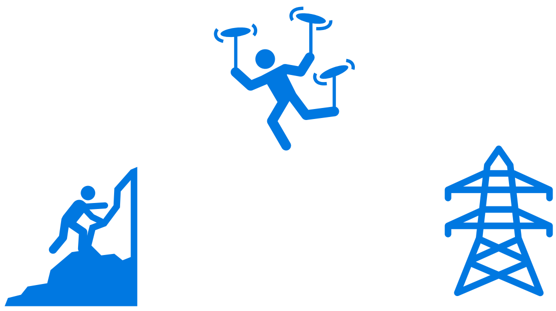
Possible barriers learned from CP Kelco

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.



Viegand Maagøe

Thanks

Juniorprojektleder

Morten Sandstrøm Petersen
Civilingeniør

+45 60 29 78 03

msp@viegandmaagoe.dk

Viegand Maagøe

Nørre Farimagsgade 37

1364 København K.

Tel. +45 33 34 90 00

Energy Optimization and Electrification Study of a Brewery, Harboe

Nasrin Arjomand Kermani[a], Andreas Helk[b], *Riccardo Bergamini[a], Brian Elmegaard[a], Fridolin Müller Holm[b]*

[a]Themal Energy Section, Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, Bygning 403, 2800 Kgs. Lyngby, Denmark

[b]Viegand Maagøe A/S, Nørre Farimagsgade 37, 1364 København K, Denmark

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.

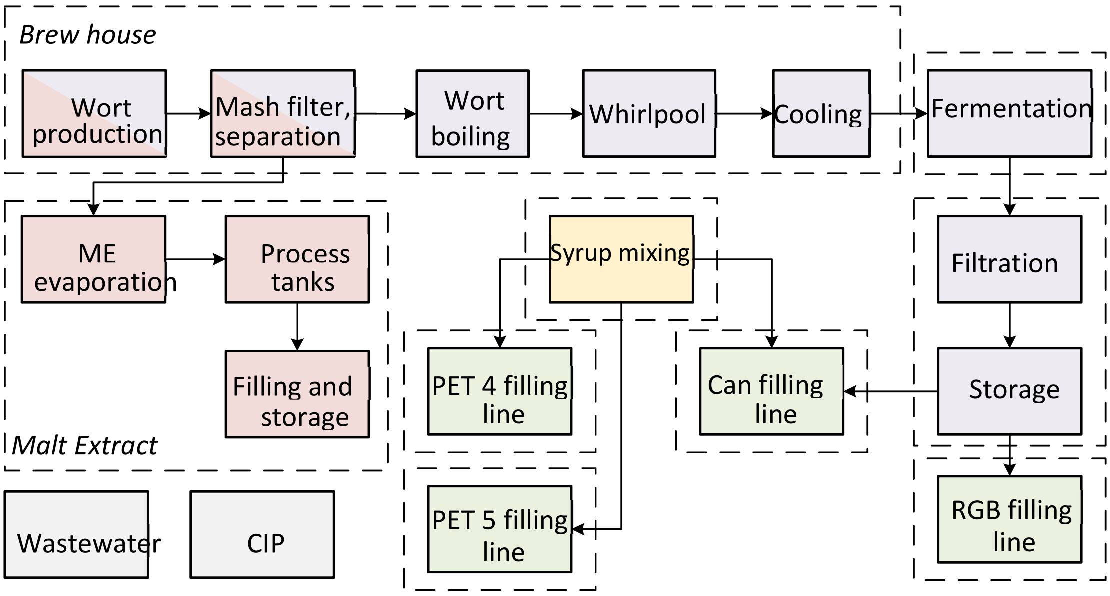


Figure-1: Simple block presentation of the processes at Harboe brewery

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

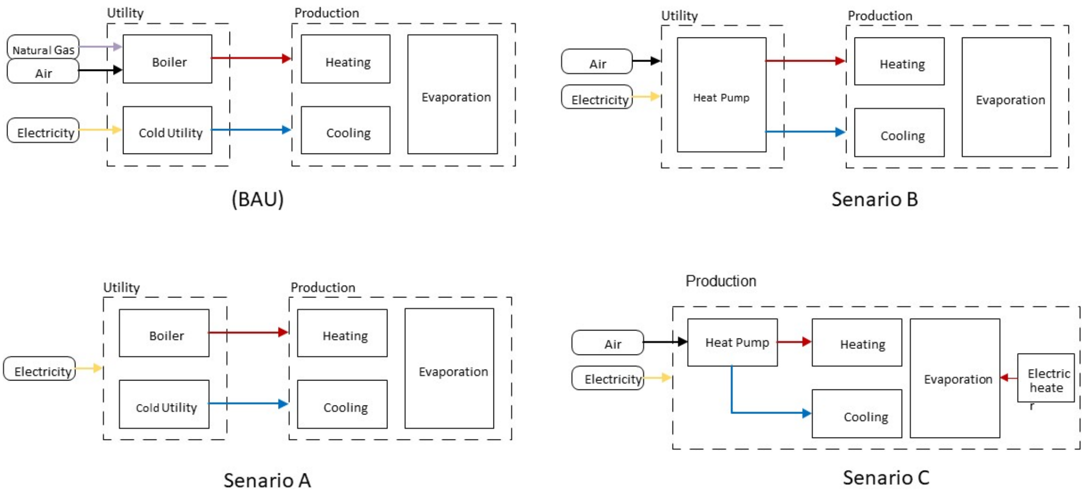


Figure-2: the overall utility and production structure in business as usual (BAU) and selected scenarios A, B, and

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.

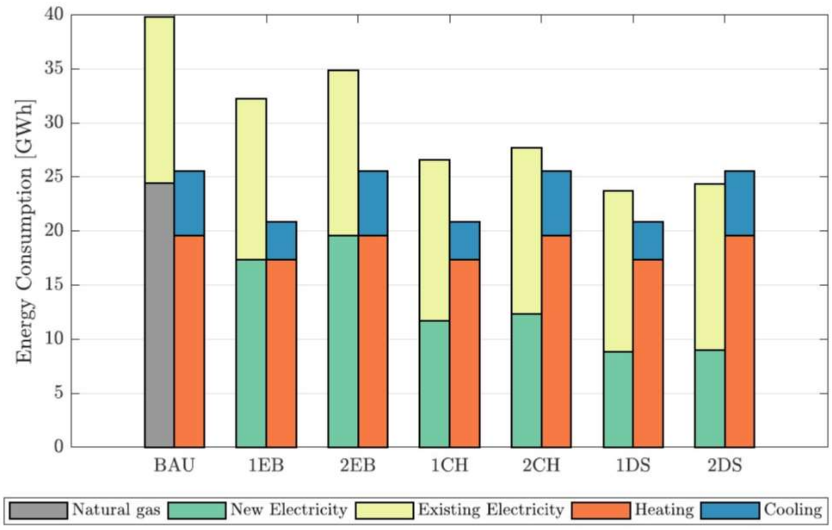


Figure-3: Total energy use of the scenarios in the screening phase, 1 and 2 represents the scenarios with and without hear recovery respectively

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.

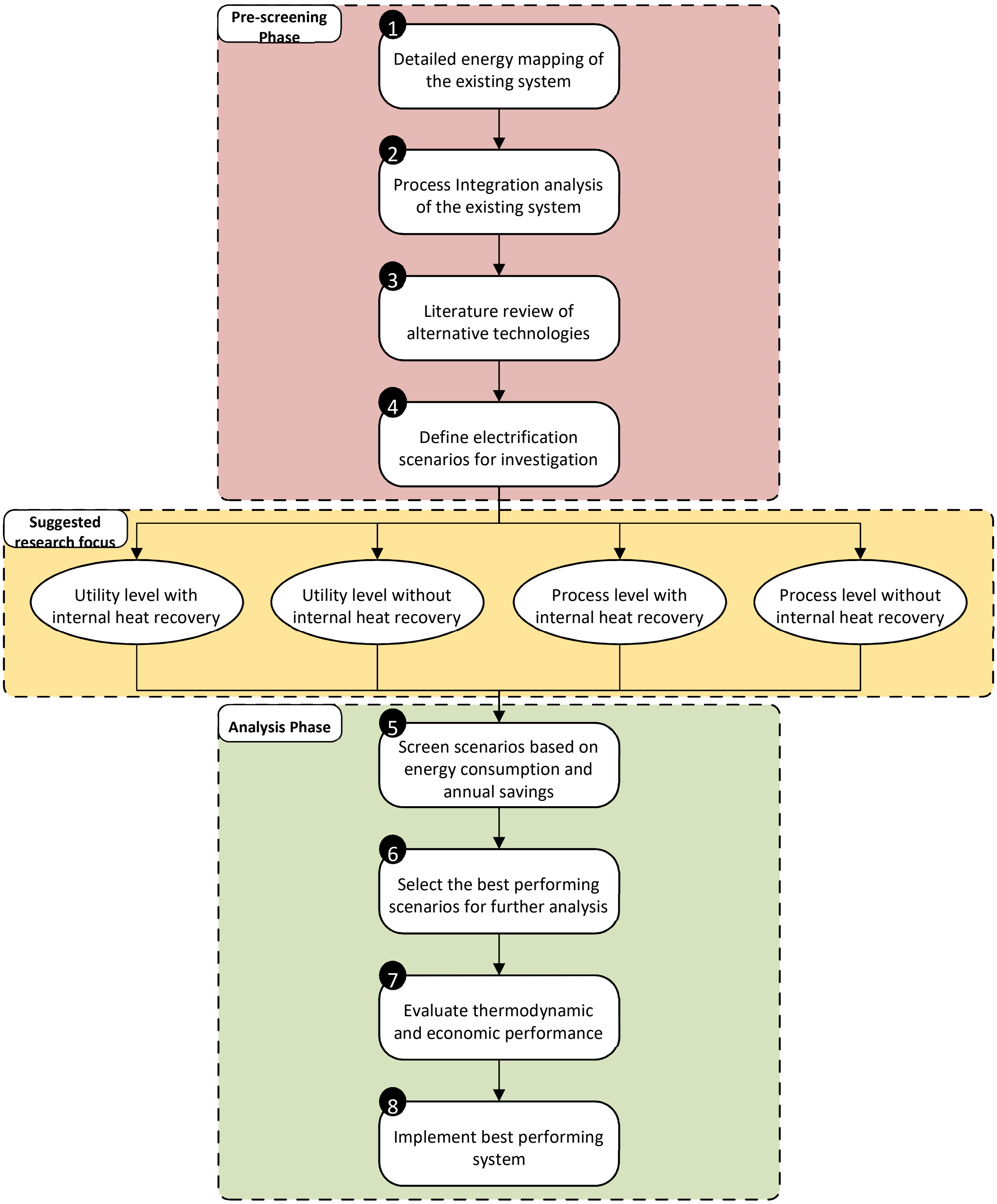


Figure-4 Process scheme of the suggested general electrification Strategy

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.

Bibliography

[1] Andrea Helk, ”Energy Optimization and Electrification of Study of a Brewery”, Master Thesis, Department of Mechanical Engineering, Technical University of Denmark, 2020

[2] Harboes Bryggeri A/S, “Årsrapport 2018-2019”, 2019.

[3] Harboe Bryggeri A/S, “About Harboe - strategy and financial targets”, http: / / harboes - bryggeri.dk/en/about-harboe/strategy, [Accessed: 06-03-2020].

[4] I. C. Kemp and A. Deakin, “The cascade analysis for energy and process integration of batch processes. i: Calculation of energy targets”, Chemical engineering research & design, vol. 67, no. 5, pp. 495–509, 1989.

[5] Danish Energy Agency, “Standardfaktorer for brændværdier og CO2-emissionsfaktorer til brug for rapporteringsåret 2019”, 2020.

[6] P. Capros, A. De Vita, and N. Tasios et al., “EU Reference Scenario 2016 - Energy, transpor and GHG emissions Trends to 2050”, European Commission, Tech. Rep., 2016.

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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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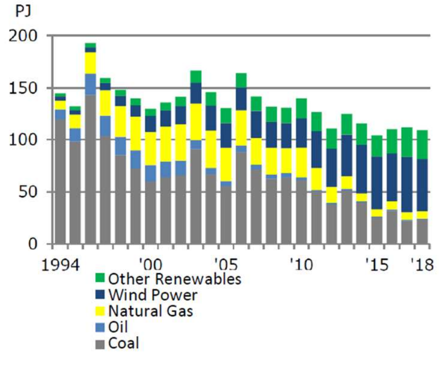
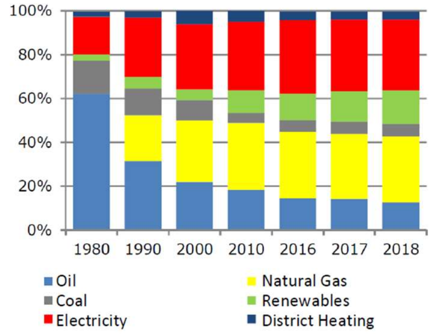
Motivation

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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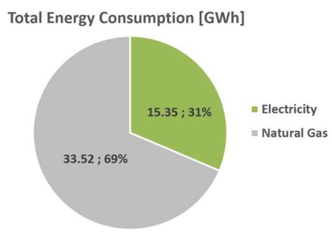
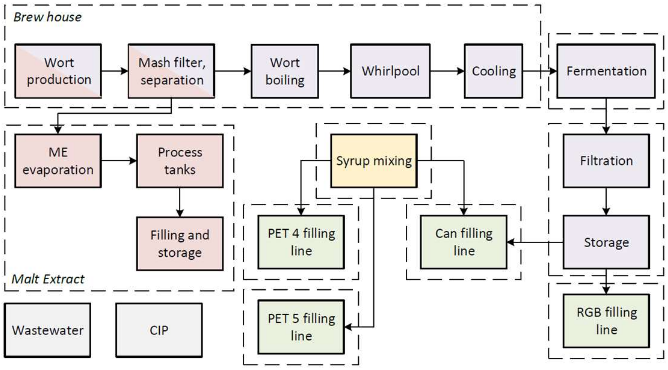
2. Background

The Harboe Brewery

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





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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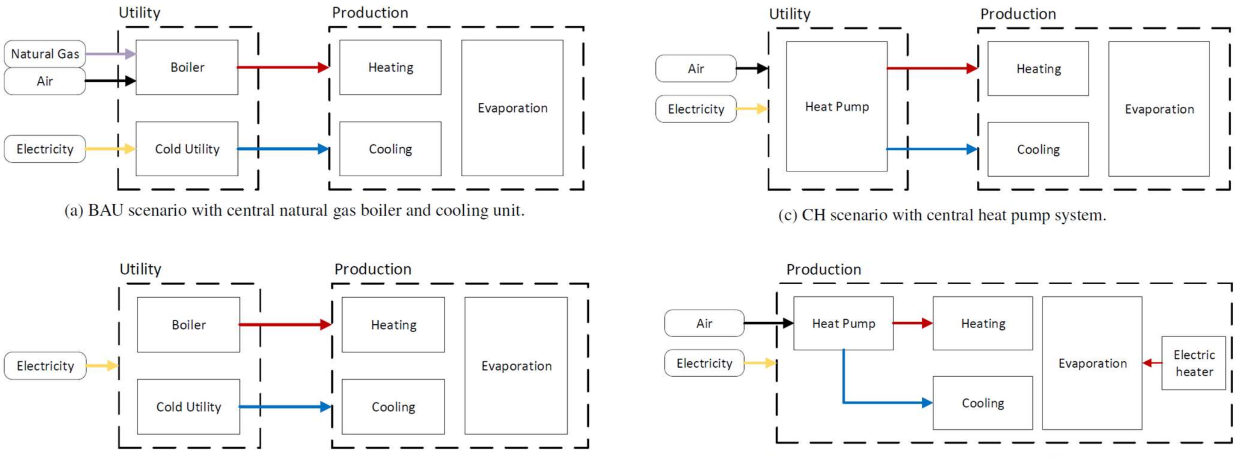
Structure of Scenarios



(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.

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4. Results

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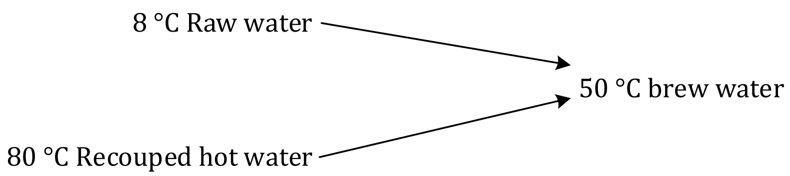
Process Integration Analysis

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

Before:



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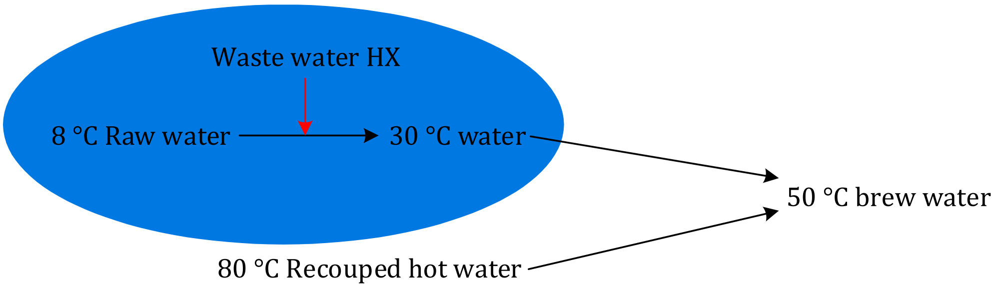
Process Integration Analysis

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

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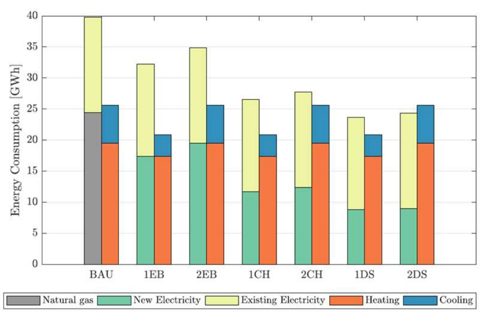
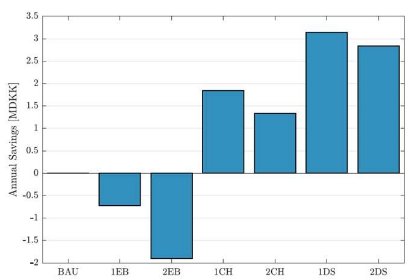
Electrification Analysis

Scenario screening





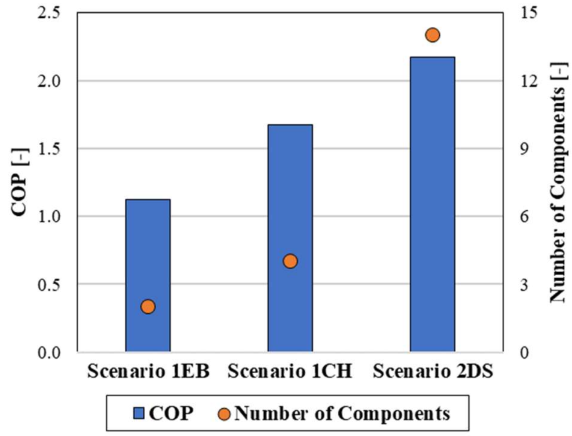
Scenario	Description	Reduced energy consumption [GWh]	Annual Savings [MDKK]
1EB	Electric Boiler with heat integration	7.53 GWh (19%)	-0.72
1CH	Centralized HP with heat integration	13.21 GWh (33%)	1.84
2DS	Decentral System without heat integration	15.44 GWh (39%)	2.84

Electrification

Energy analysis

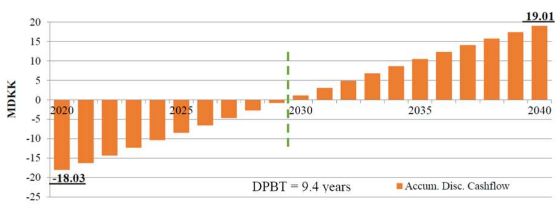
Trade-off between thermodynamic performance and number of components.

- Heat pumps in decentral system have significantly smaller temperature lifts

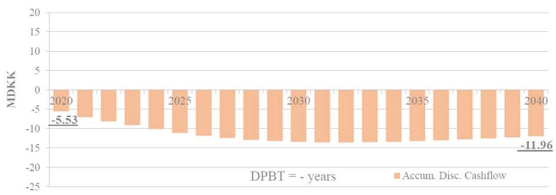


Electrification

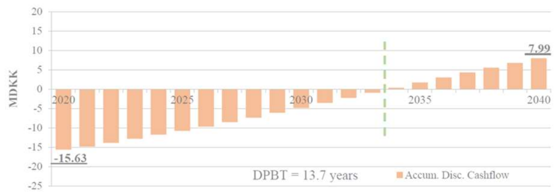
Feasibility study



(c) Scenario 2DS

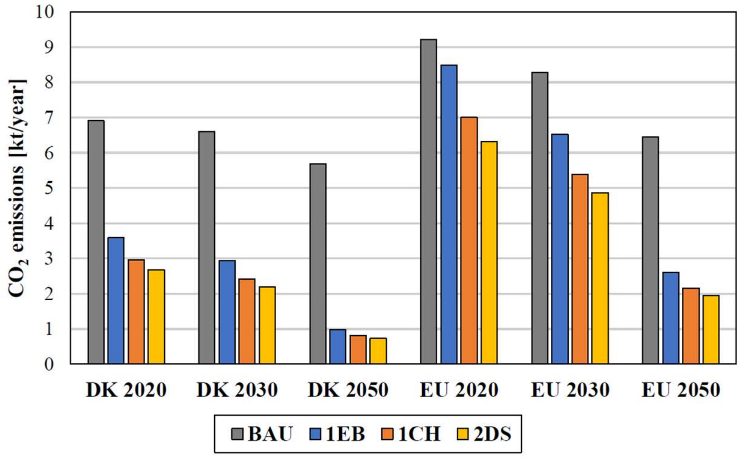


(a) Scenario 1EB



(b) Scenario 1CH

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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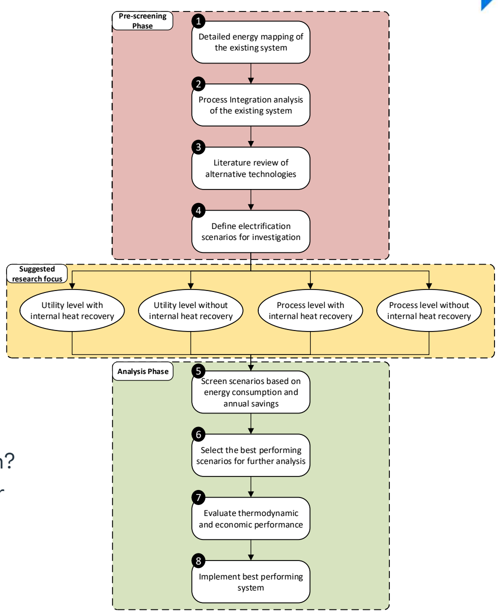
General Electrification Strategy

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!

Juniorrådgiver
Andreas Helk
Civilingeniør
+45 31 75 17 05
ahe@viegandmaagoe.dk

Viegand Maagøe
Nørre Farimagsgade 37
1364 København K.
Tel. +45 33 34 90 00

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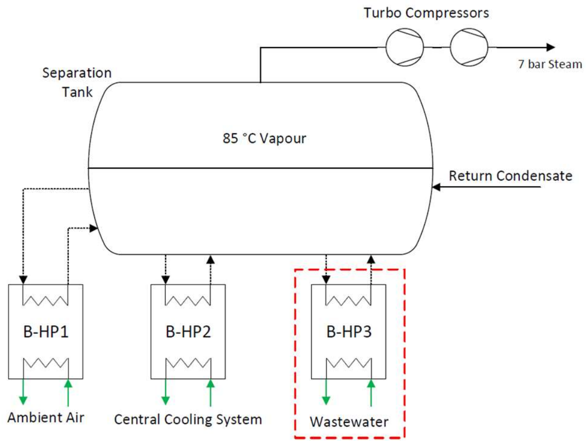
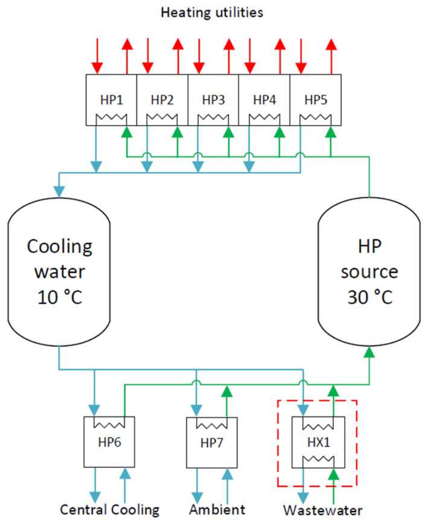
7. Appendix

Additional slides for break-out room

Modeling approach

- All heat pumps modeled with a Lorentz COP approach





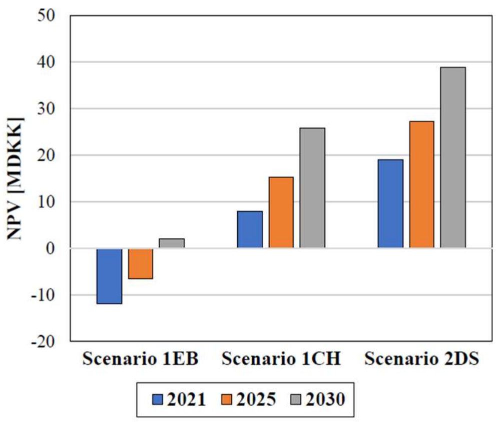
Process Integration

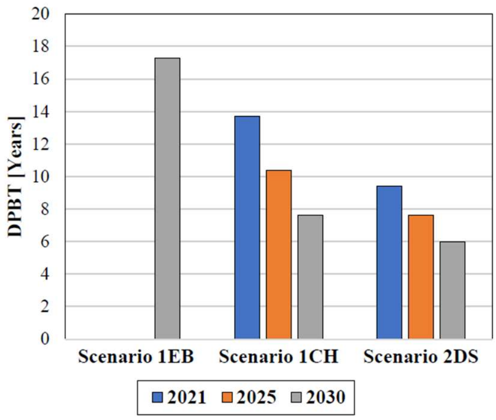
Economic evaluation

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

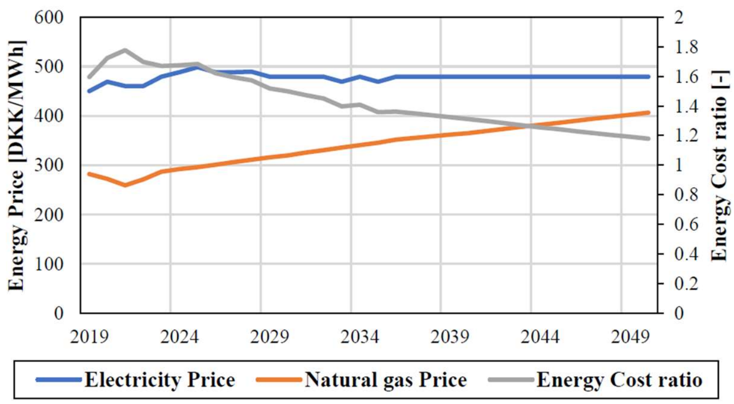


Figure 4.7: Projection the natural gas- and electricity prices and the ratio between the prices.

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Emission Factors

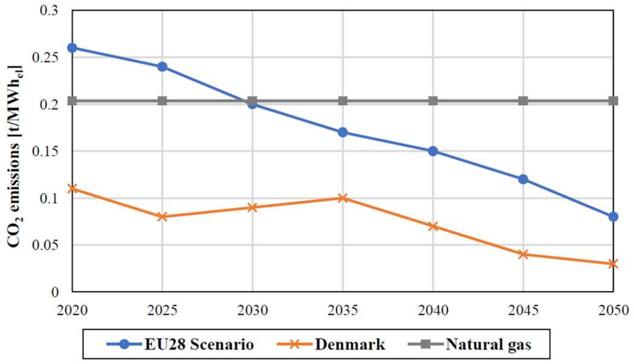

Figure 4.8: CO_2 emission factors of natural gas and the electricity mix of Denmark and the EU-28 reference scenario.

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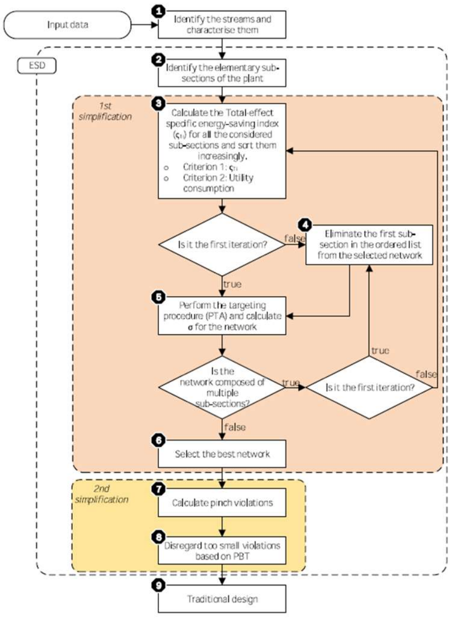
Process Integration

ESD 1st simplification



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.

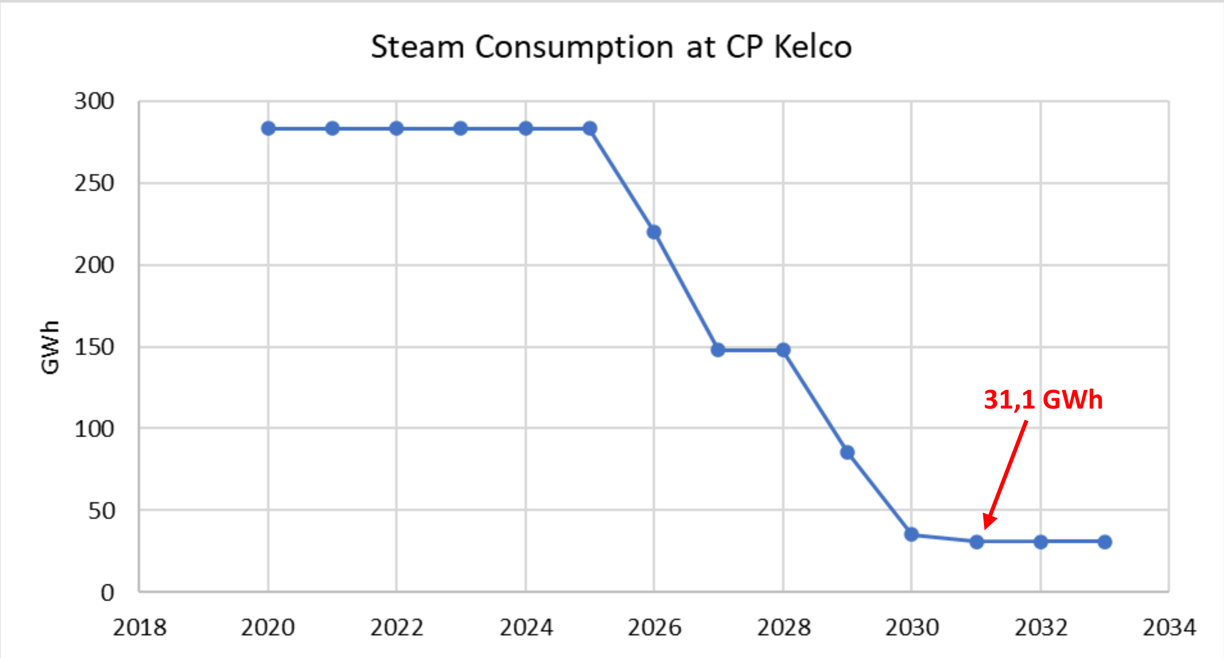


Figure 1: Projected steam consumption at the CP Kelco facility.

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.

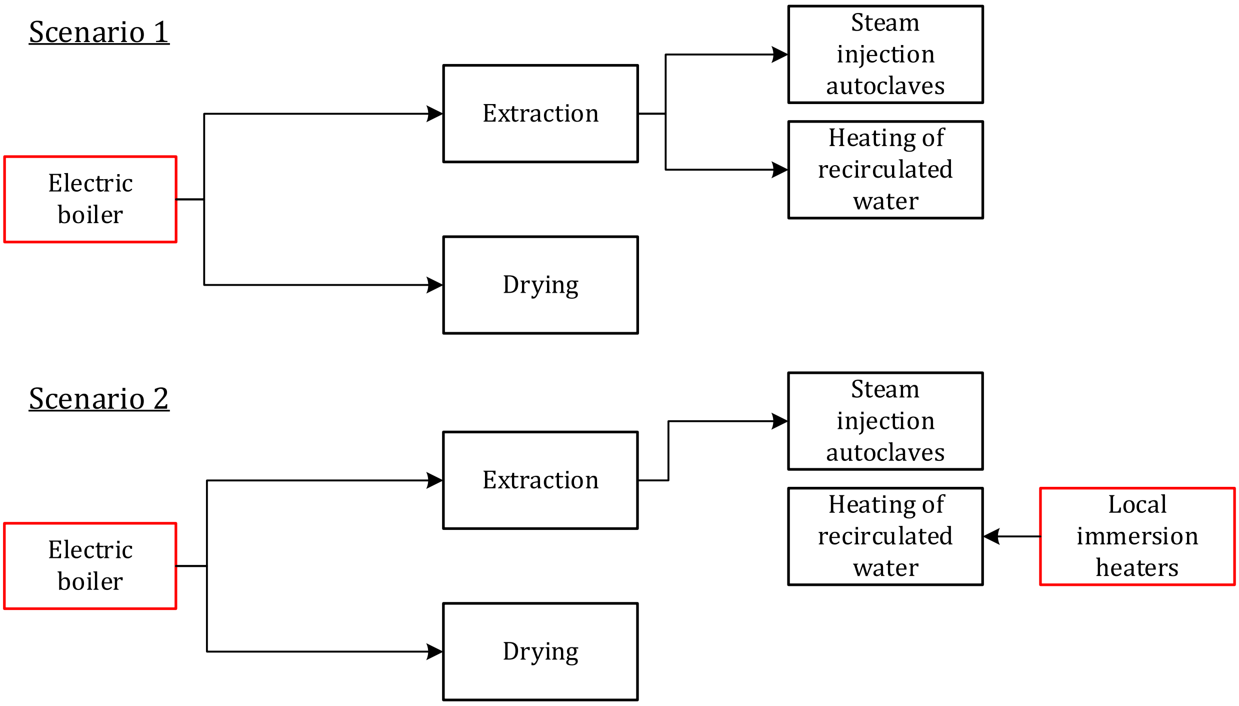


Figure 2: Schematic representation of the two scenarios

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.

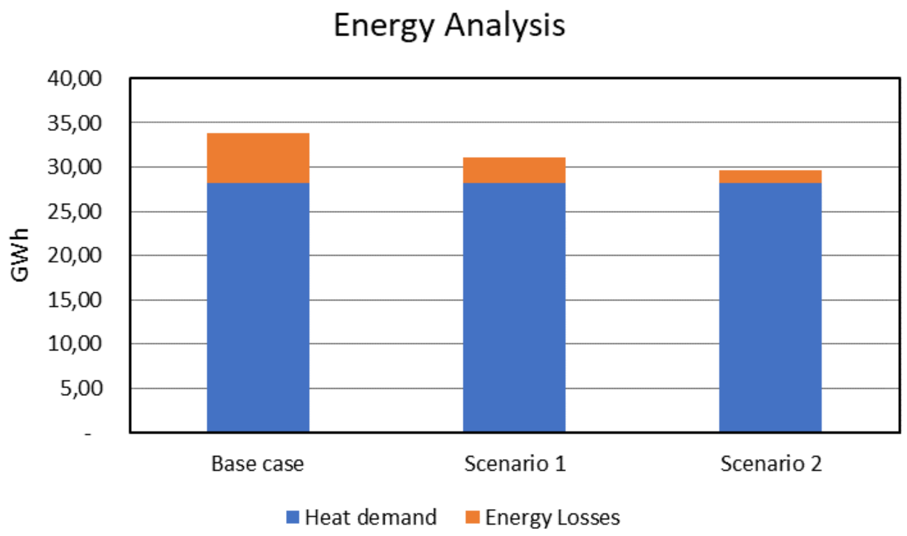


Figure 3: Energy analysis of the scenarios.

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.

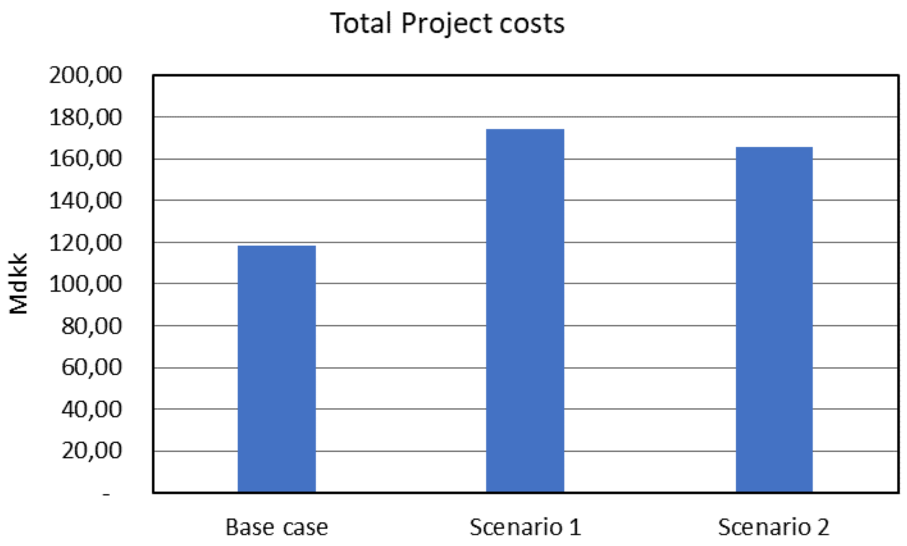


Figure 4: Total project costs over 10 years of operation.

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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].

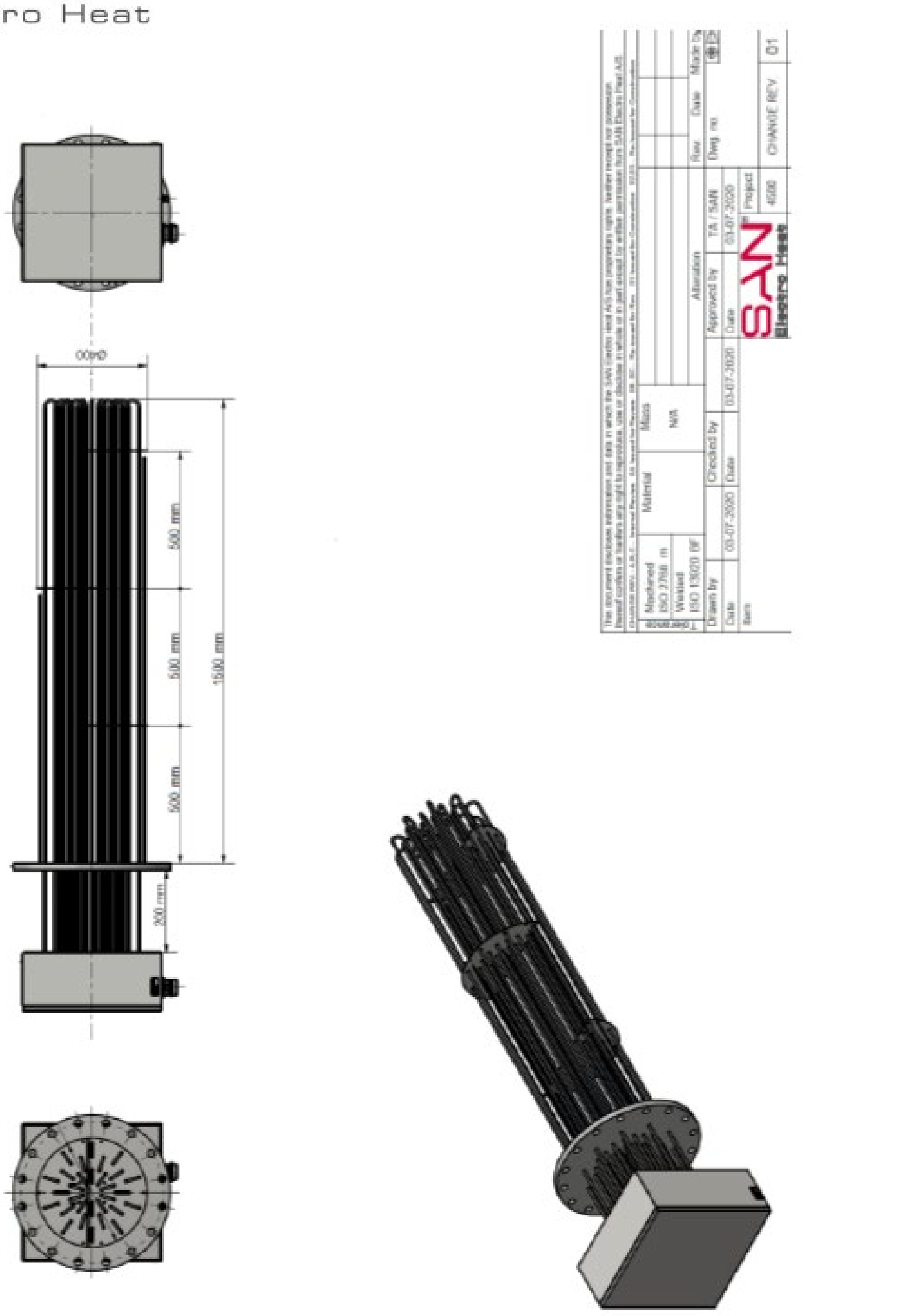
[2] Danish Energy Agency, "Basisfremskrivning 2020," Danish Energy Agency, 2020.

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

9 Appendices

A. Immersion Heater

Member of the NIBE Group



SAN Electro Heat a/s
Gillelejevej 30b
DK-3230 Græsted

T: +45 48 39 88 88
F: +45 48 39 88 98

info@san-as.com
www.san-as.com

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

Viegand Maagøe

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

Viegand Maagøe

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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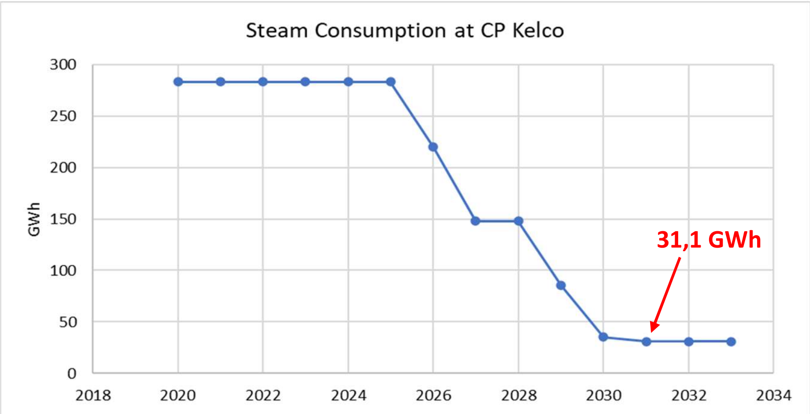
Projected Steam consumption

- 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



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3. Scenario Descriptions

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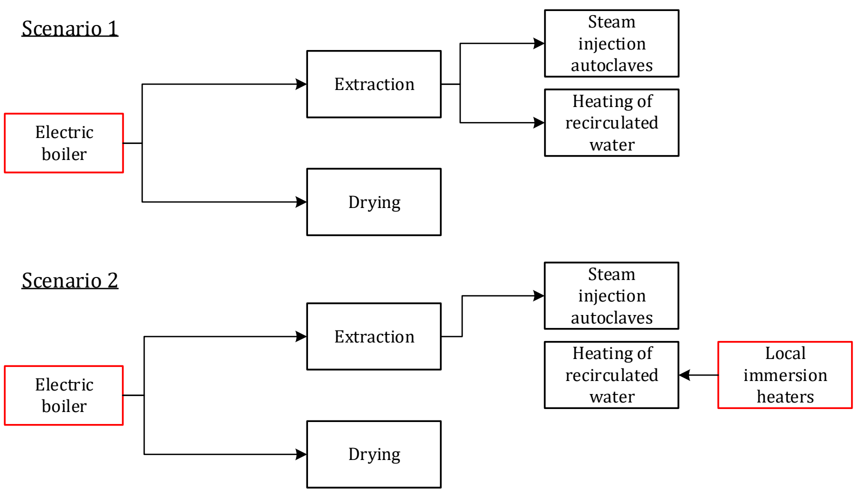
General Overview



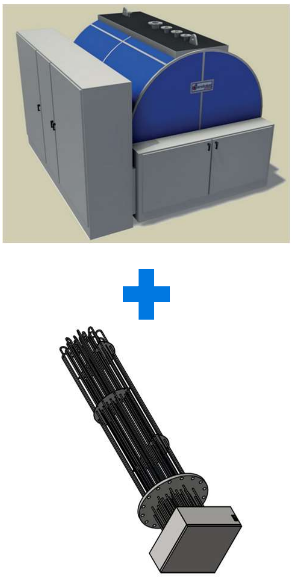
Scenario 1

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**

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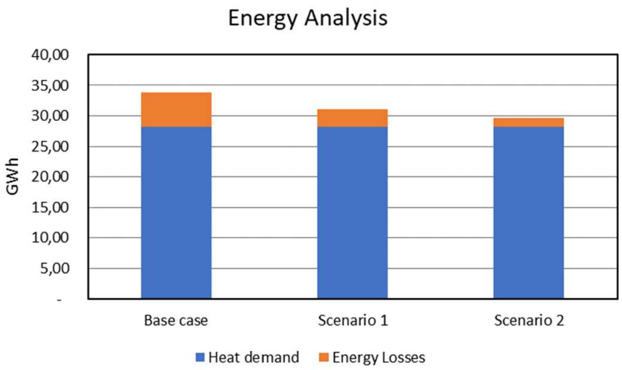
4. Energy Analysis

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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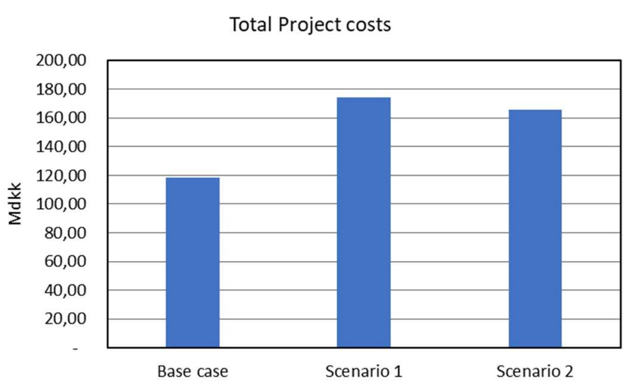
Analysis of the Total Project Costs

- 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



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6. Discussion

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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

7. Additional Solutions

Electric heating solutions for industrial high temperature processes

SAN Electro Heat

SAN PROCESS HEATING

Tubular heating technology

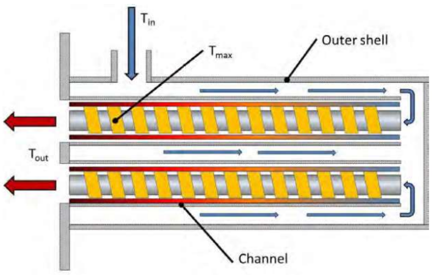
- Traditional resistance heating element for high power high flow solutions.
- Used for gas heating in the 5kW to +10 MW, max 650°C

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.

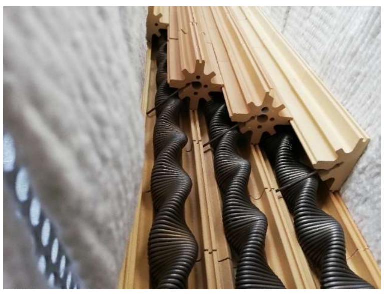


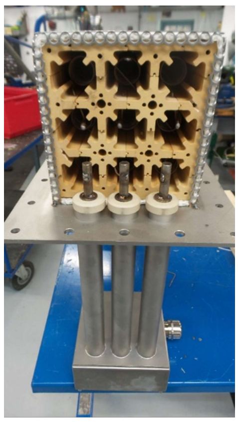
SAN Electro Heat

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!

SAN Electro Heat

Juniorrådgiver
Andreas Helk
Civilingeniør
+45 31 75 17 05
ahe@viegandmaagoe.dk

Gillelejevej 30b
DK-3230 Graested
Denmark
Tel.: +45 48 39 88 88
Fax: +45 48 39 88 98
www.san-as.com
info@san-as.com

Viegand Maagøe
Nørre Farimagsgade 37
1364 København K.
Tel. +45 33 34 90 00

Volatile and Heat Recovery System Design - Labotek Case Study

Nasrin Arjomand Kermani[a], Fabian Bühler[a], Lars Ingolf Hansen[b], Peter Jessen Jürgensen[b], Brian Elmegaard[a]

[a]*Themal Energy Section, Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, Bygning 403, 2800 Kgs. Lyngby, Denmark*

[b]*Labotk A/S, Strøbjergvej 29, 3600 Frederikssund, Denmark*

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.

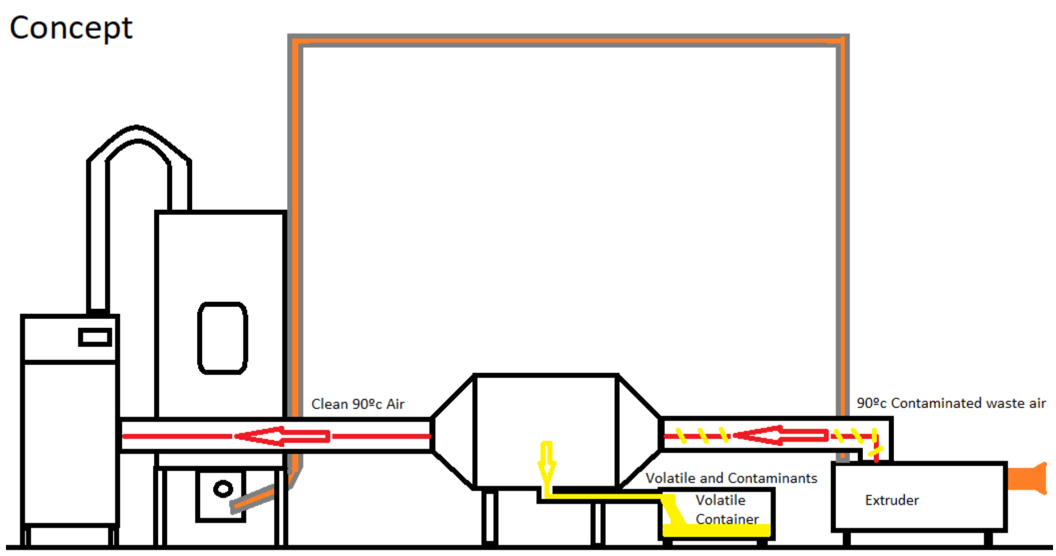


Figure-1: Proposed concept by Labotek A/S called "Volatile and Heat Recovery System (V-EHR)"

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 m³/h, 3000 m³/h, and 5000 m³/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.

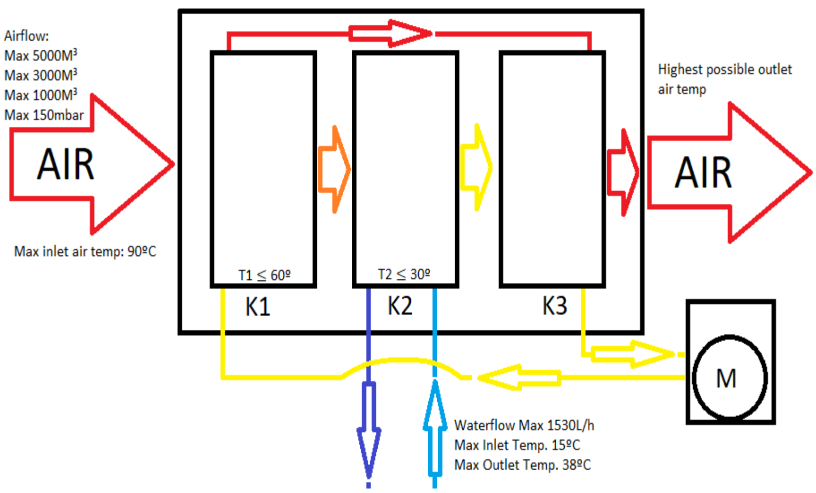


Figure-2: Preliminarily design of the proposed system consists of three heat exchangers connected in a series

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.

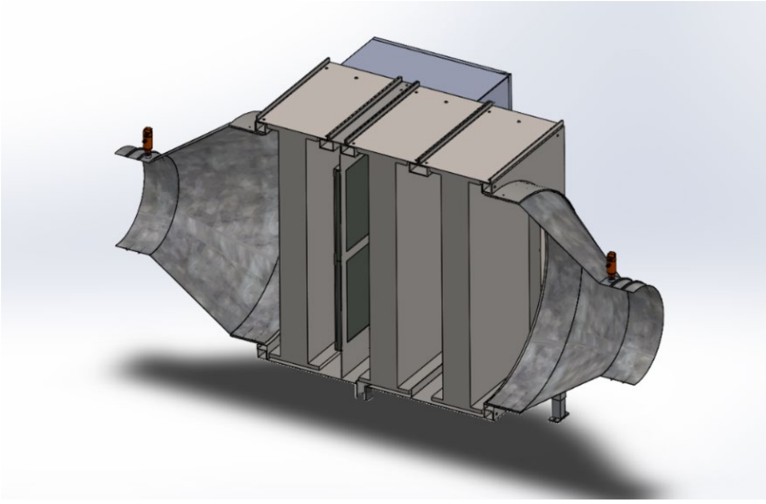


Figure-3: The 3D configuration of the proposed prototype developed by Labotek A/S

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.

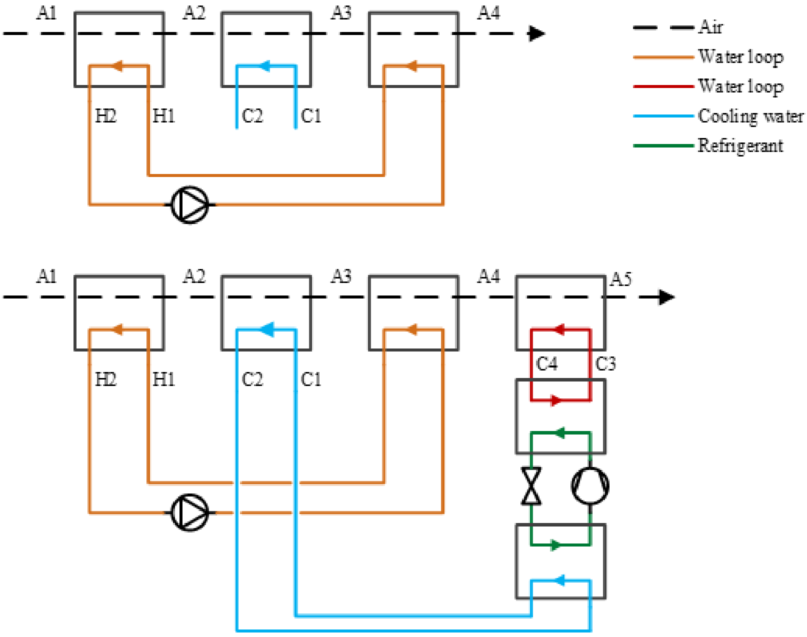


Figure-4: drawing of the system for the two cases (upper) direct heat recovery and (lower) heat pump integration, consists of air and water loops for cooling and heating purposes

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.

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

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

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

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 $\dot{Q}_{\text{sink}}$ 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.

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

Where $h_{\text{air,in}}$ is the specific enthalpy of the air at the inlet the first heat exchanger and $h_{\text{air,out}}$ 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. $h_{\text{air,0}}$ 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.

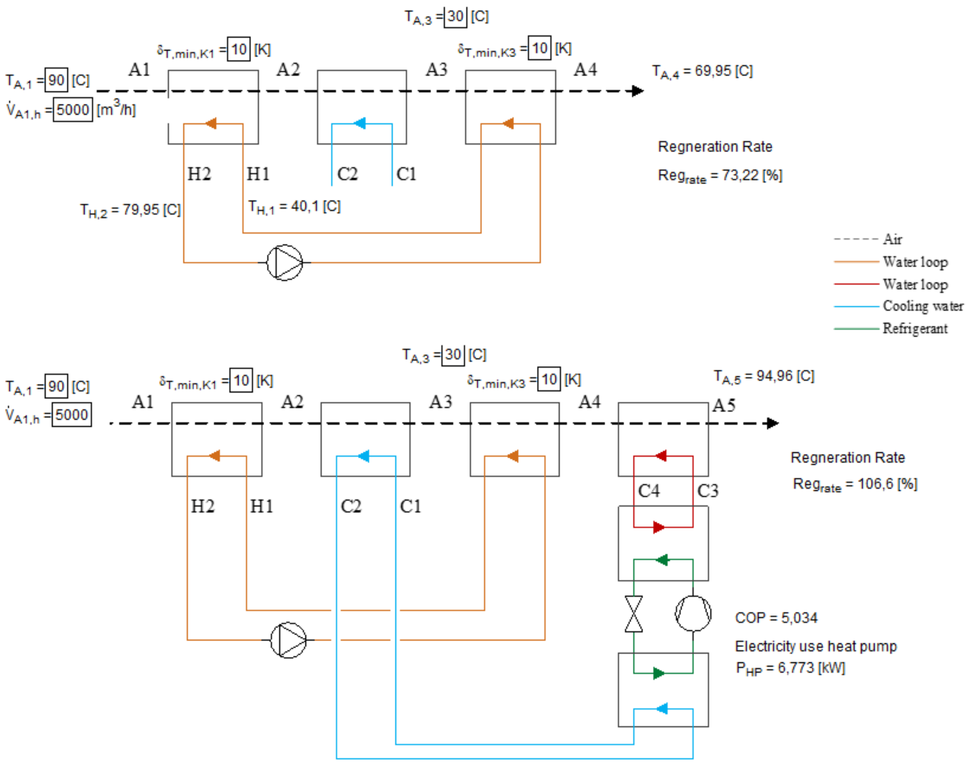


Figure-5: Results obtained from EES model, for the two cases (upper) direct heat recovery and (lower) heat pump integration for 90 °C and 5000 m³/h inlet airflow

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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Bibliography

[1] Iwata T. Biodegradable and bio-based polymers: Future prospects of eco-friendly plastics. Angew Chemie - Int Ed 2015;54:3210–5. doi:10.1002/anie.201410770.

[2] Müller B, Fritjof Nansen Institute. The Global Climate Change Regime: Taking Stock and Looking Ahead. vol. 2003. London: of International Co-operation on Environment and Development; 2002.

[3] Jamieson D. Public Policy and Global Warming 2016.

[4] Wolf S, Lambauer J, Fahl U, Blesl M, Voss A. Industrial heat pumps in Germany - potentials , technological development and application examples. ECEEE 2012 Summer Study - Energy Effic Ind 2012:543–50.

Volatile and Heat Recovery System

Labotek Case Study

Nasrin Arjomand Kermani
nasker@mek.dtu.dk

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).

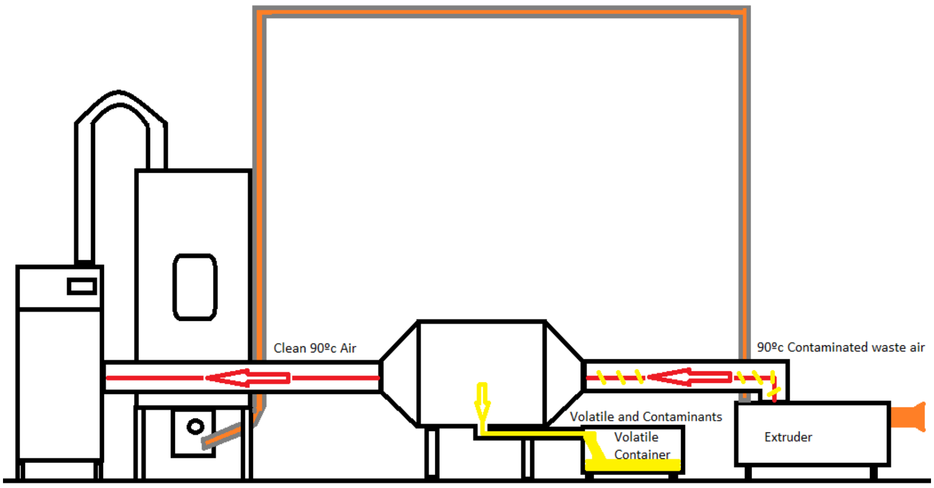
Labotek Power in Plastics

Source: https://labotek.com/

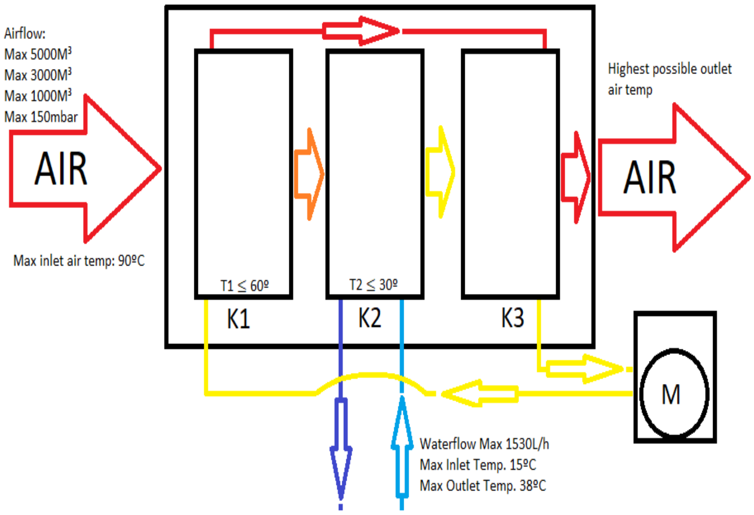
Labotek Proposed Concept

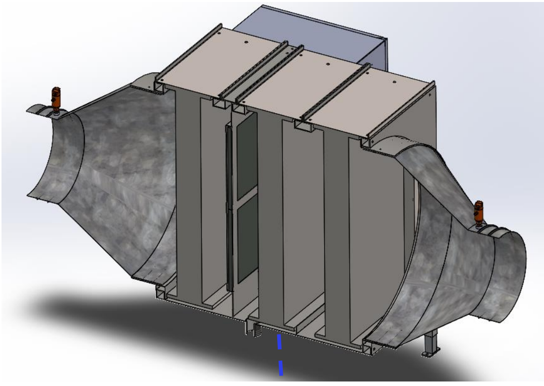
Volatile and Heat Recovery system (V-EHR)

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:

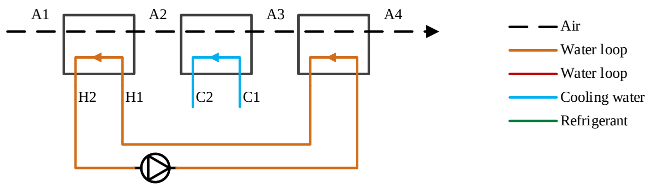
- Reduces of the total energy consumption, consequently reduces CO_2 emission in the use-phase.
- Provides the possibility of offering not only a product, but also a solution that can be optimally adopted and integrates the offered product to the existing facilities

Method

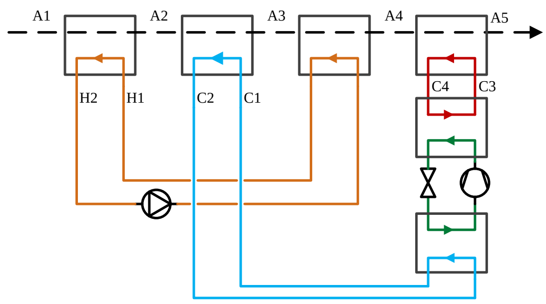
- Process analysis and data collection
- Energy analysis
- Energy optimization
  - » Minimum of 50% regeneration of initial energy
  - » Maximum of 30°C in the middle HEX with cooling process
  - » Minimum of 50-60°C at the outlet
- Heat pump integration

DTU EES-Model

Heat exchanger model (Direct)

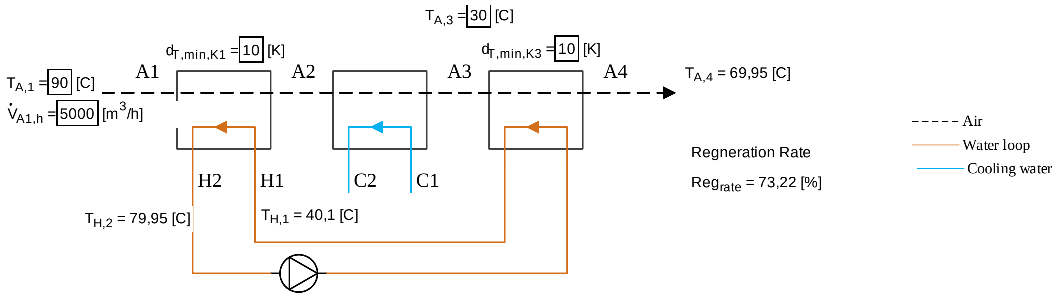


Heat exchanger model (Heat pump)



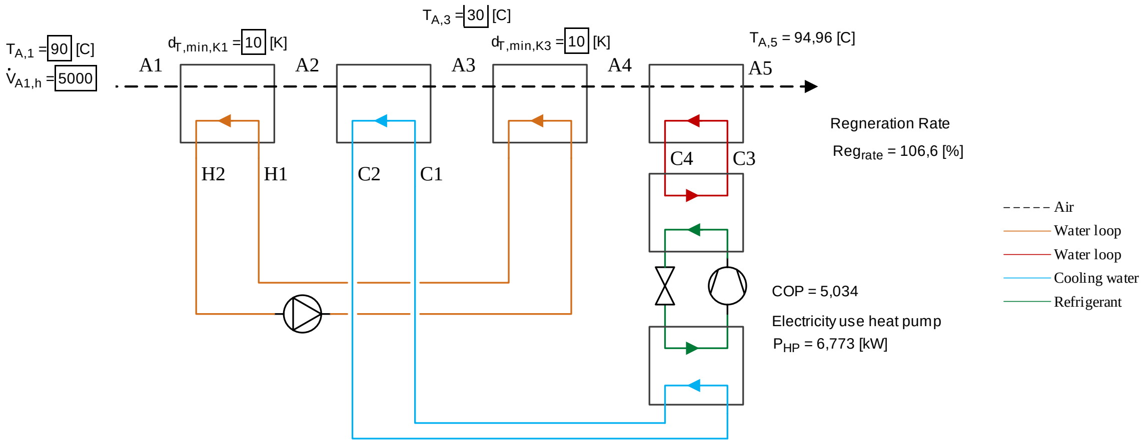
Outcome of DTU EES Model

Heat exchanger model (Direct)



Outcome of DTU EES Model

Heat exchanger model (Heat pump)



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Labotek Final Product

3 Installations with heat recovery in Egypt

DTU

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

Labotek: Peter Jessen Jürgensen (PJJ@labotek.dk)
DTU: Nasrin Arjomand Kermani, Fabian Bühler, Brian Elmegaard (be@mek.dtu.dk)

UNIVERSITÀ DEGLI STUDI DI PADOVA

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

UNIVERSITÀ DEGLI STUDI DI PADOVA

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*

DTU

UNIVERSITÀ DEGLI STUDI DI PADOVA

CASE STUDY

Carlsberg Group

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

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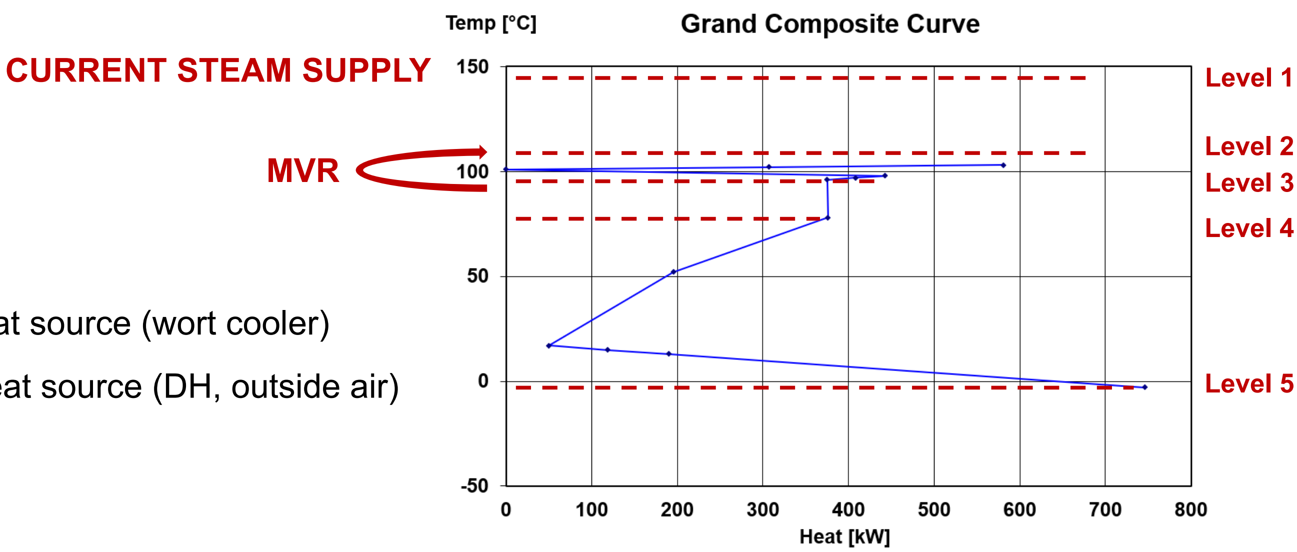
TIME AVERAGE MODEL

Carlsberg Group

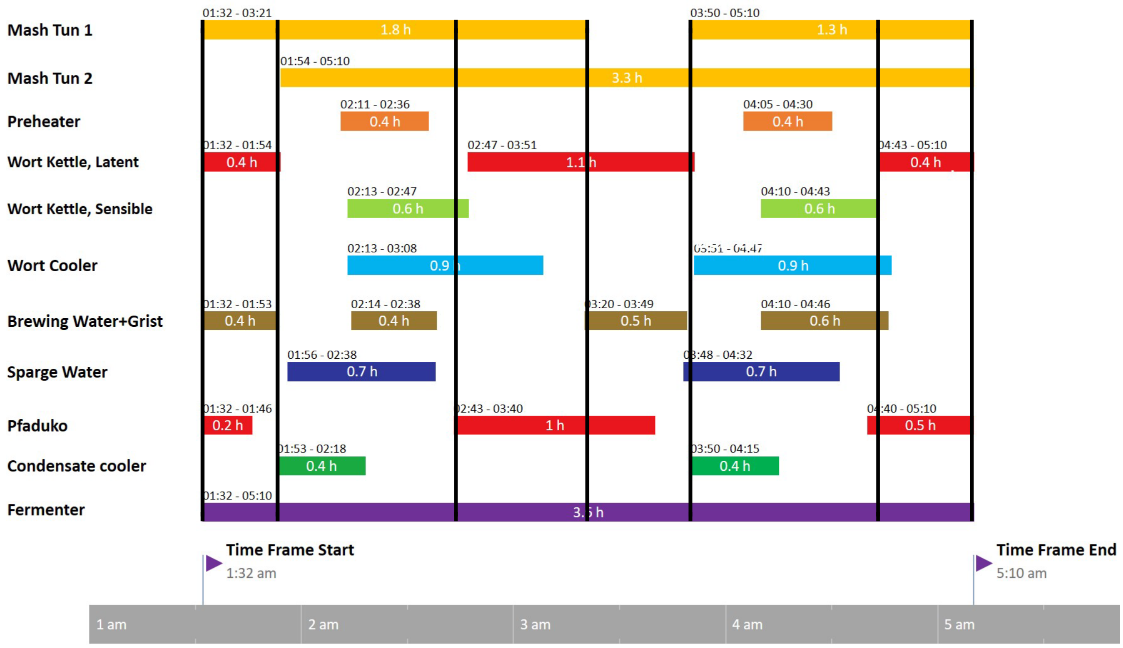
➢ Potential energy savings → 59%



HTHP

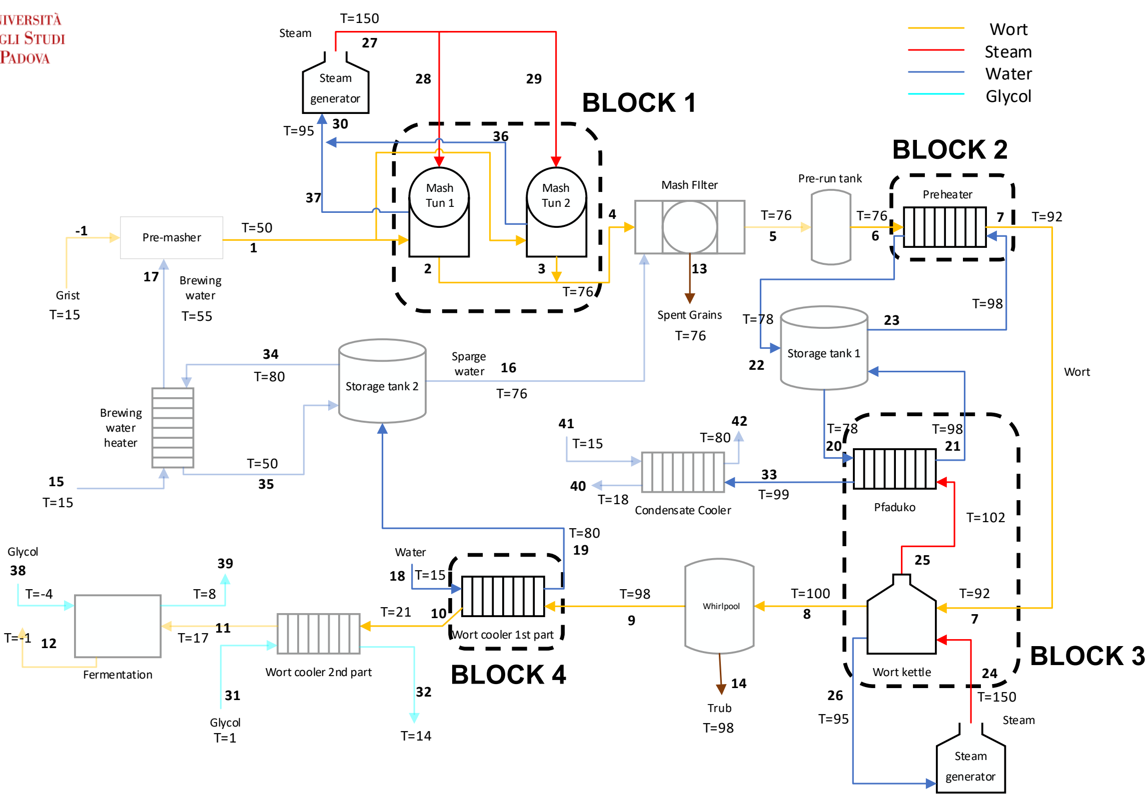
- Internal heat source (wort cooler)
- External heat source (DH, outside air)

TIME SLICE MODEL



- 6 slices
- Energy savings: 2.38%

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



CONFIGURATION 1A: MVR & HTHP

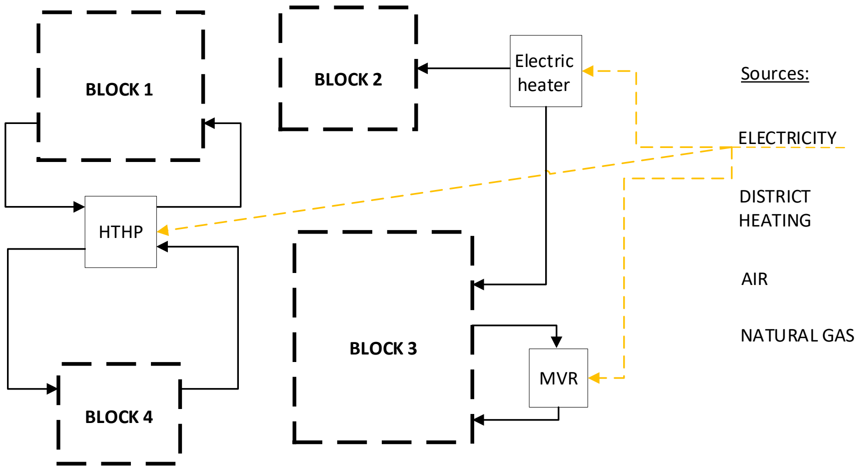
- Heat source → water from wort cooler
- Electric heater to supply the lack of heat

⬇

Complete elimination of steam supply from natural gas

⬇

CO_2 reduction: -1.8 million kg/year

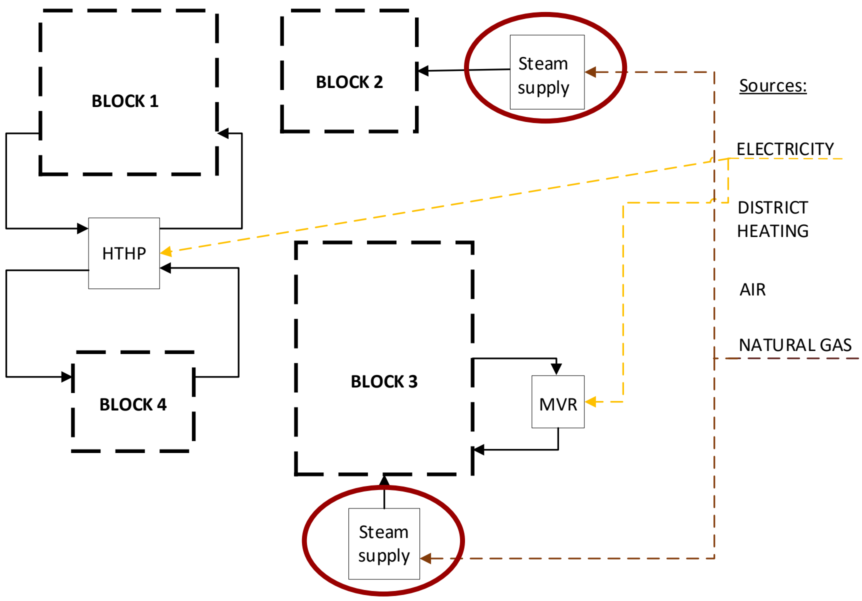


CONFIGURATION 1B: MVR & HTHP

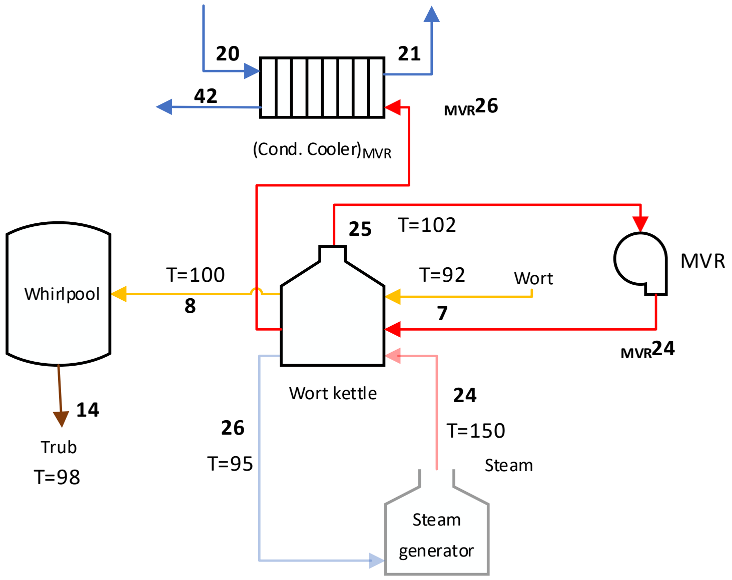
- Heat source → water from wort cooler
- No electric heater

⬇

CO_2 reduction: -792,000 kg/year



MECHANICAL VAPOUR RECOMPRESSION



PERFORMANCES

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

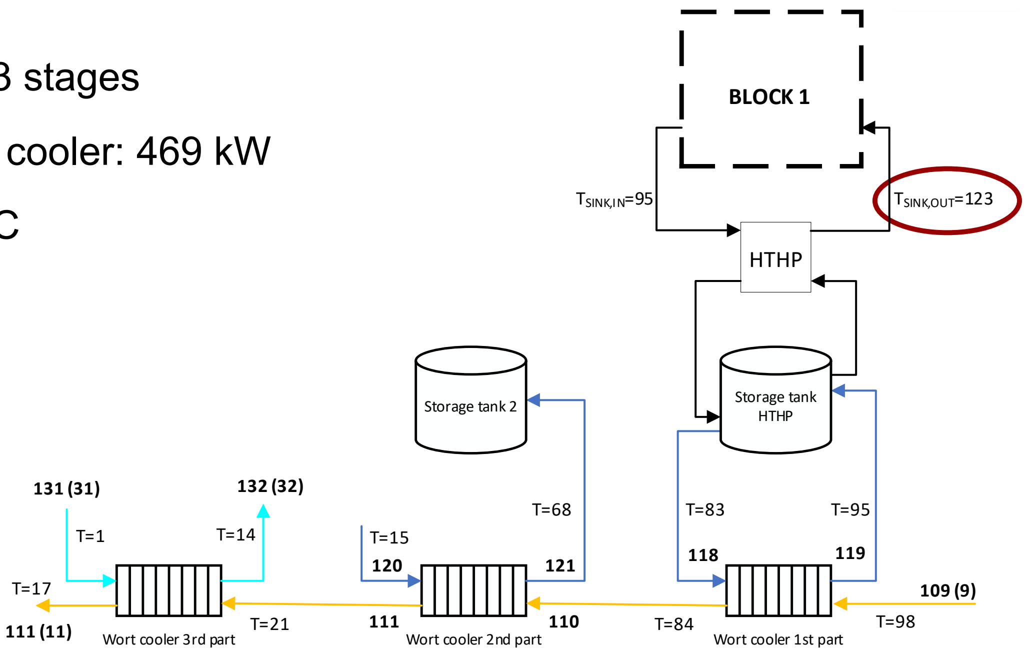
Heat partially recovered at the pfaduko

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



CONCLUSION

GOALS

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

ZERO CARBON FOOTPRINT

→ *Reduction in natural gas consumption (1764 GWh in 2019)*

→ *Electrification of the heat supply in the brewhouse*

THANK YOU

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

Kousidis V.[1], *Zühlsdorf B.*[2], *Bühler F.*[1], *Elmegaard B.*[1]

[1] Technical University of Denmark, Department of Mechanical Engineering, Lyngby, Denmark
kousverg@gmail.com
[2] Danish Technological Institute, Energy and Climate, Aarhus, Denmark

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.

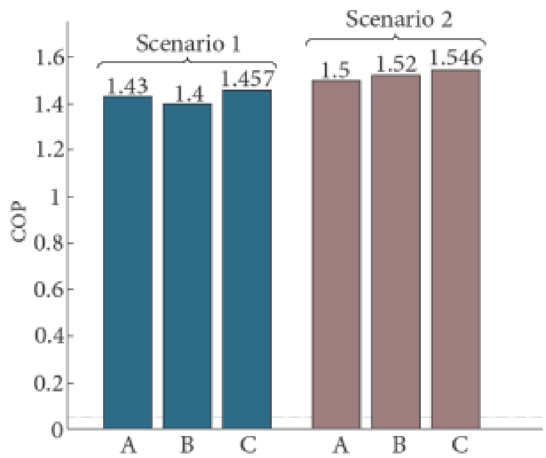


Figure 1. Average optimized COP of Sub-Scenarios

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.

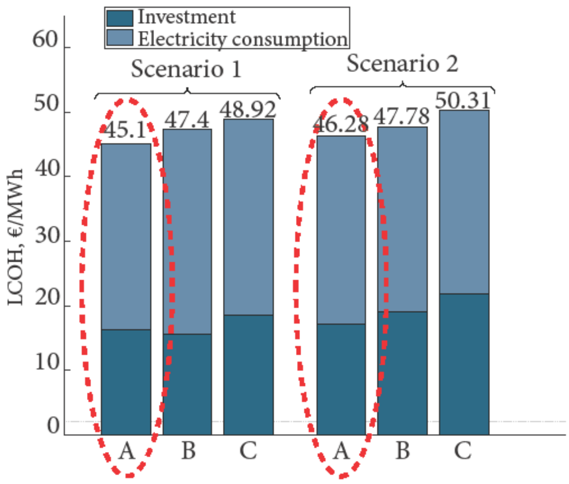


Figure 2. LCOH comparison between sub-scenarios

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].

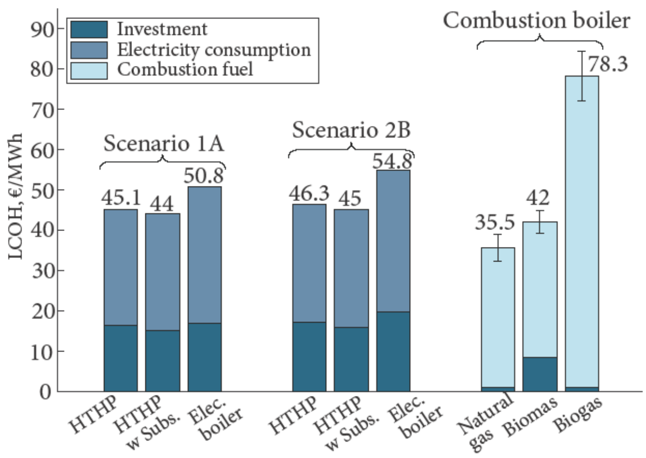


Figure 3. LCOH of HTHPs with and without subsidy and of conventional technologies

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.

References

[1] European Commission. Climate strategies and targets: 2030 climate and energy framework. URL: https://ec.europa.eu/clima/policies/strategies/2030. Last Visited on: 09.04.2019.

[2] European Commission. A policy framework for climate and energy in the period from 2020 to 2030. Technical report, (2014).

[3] The Danish Government. Energy strategy 2050 - from coal, oil and gas to green energy. Technical report, (2011).

[4] Bühler F., Zühlsdorf B., and Elmegaard B. Industrial energy demand and excess heat in Denmark. In *International Workshop on High Temperature Heat Pumps*, Copenhagen, Denmark, 2017.

[5] Kousidis V. *Analysis and optimization of high-temperature heat pumps in combination with renewable electricity sources*. Technical University of Denmark (DTU), Master Thesis, 2019.

[6] Chaudhuri U.R. *Fundamental of Petroleum and Petrochemical Engineering*. CRC Press, Taylor and Francis Group, 2011.

[7] Chawla A. *Energy Optimization at Equinor Refining Denmark*. Technical University of Denmark (DTU), Master Thesis, 2019.

[8] Ebert W.A, Panchal C.B., Sommerscales F.C., and Toyama S. *Fouling mitigation of industrial heat exchange equipment*. Begell House, New York, 1997.

[9] Cabeza F.L., Solé C., Castell A., Oró E., and Gil A. Review of solar thermal storage techniques and associated heat transfer technologies. *Procceedings of the IEEE*, 100(2):525–538, 2012.

[10] Zühlsdorf B., Bühler F., Bantle M., and Elmegaard B. Analysis of technologies and potentials for heat pump-based process heat supply above 150ºC. *Energy Conversion and Management: X*, 2019.

[11] General algebraic modeling system (GAMS). https://www.gams.com.

[12] IEA. Application of industrial heat pumps, IEA heat pump programme annex 35, Task 3:R&D projects. pages 229–328, 2014.

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

Kousidis V.[1], Zühlsdorf B.[2], Bühler F.[1] and Elmegaard B.[1]
[1] Technical University of Denmark, [2] Danish Technological Institute

INTRODUCTION

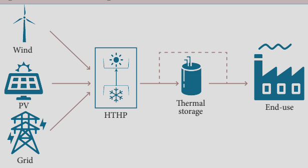
Greenhouse gas emissions are one of the main factors for global warming. Denmark contemplates to be a future completely independent of fossil fuels by 2050. For replacement of fossil fuel technologies, heat pumps consist an attractive alternative as they can be efficiently operated with renewable electricity. 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

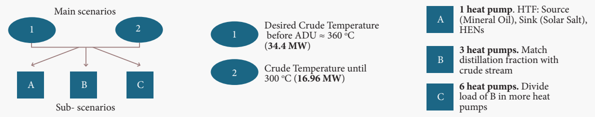
Oil and gas industry is very energy consuming since large amounts of heat are needed to increase the temperature of crude oil in high levels for the distillation to happen. Before atmospheric distillation, crude is heated in a furnace. Aim of the study was the replacement of the furnace before ADU with 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.

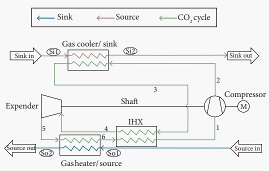
The crude oil and distillation fraction streams were selected after a retrofit was applied to preheat network.

METHODS

HEAT PUMP INTEGRATION SCENARIOS

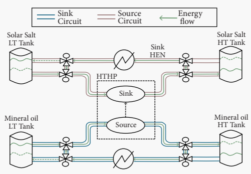


REVERSED BRAYTON CYCLE



- 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



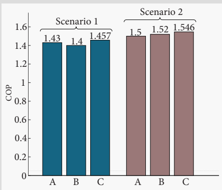
- Two tank storage configuration on both source and sink side with a low and high temperature tank.
- Applicable in Sub-Scenario A only where there are heat transfer mediums on each side.
- For heat storage integration, the heat pump should have capacity higher than the nominal requirements in heat demand.

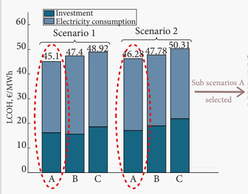
ENERGY MIX OPTIMIZATION

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

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

RESULTS



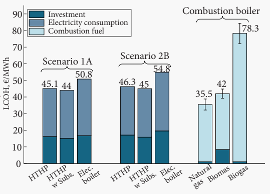


SCENARIO 1A

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 induced 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.

DTU Mechanical Engineering
Danmarks Tekniske Universitet
Nils Koppels Allé Bygning 403
DK-2800 Kgs. Lyngby, Denmark
Tlf. 4525 4131

www.mek.dtu.dk