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DTU Mechanical Engineering
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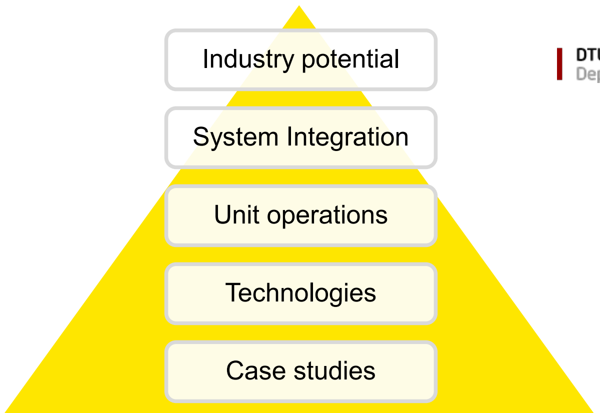
Electrification of processes and technologies for Danish Industry

Elforsk project 350-038

Final Report



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

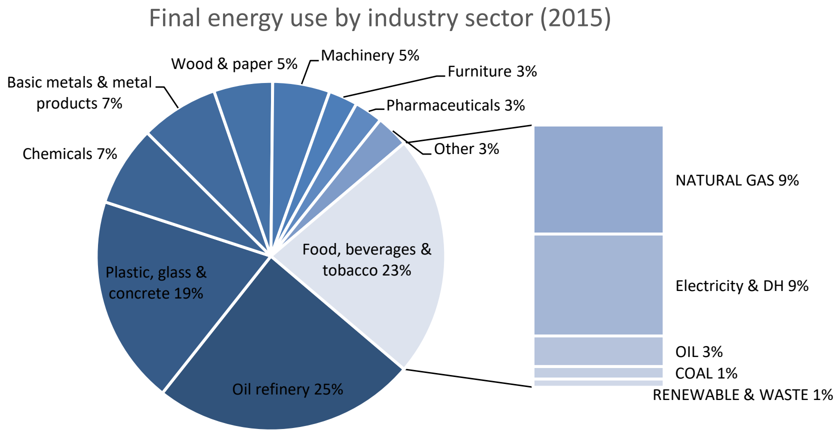


Figure 1.1: Energy use in industry by different sectors and for food and beverages in energy form. Based on data from Statistics Denmark ENE2HA [8]

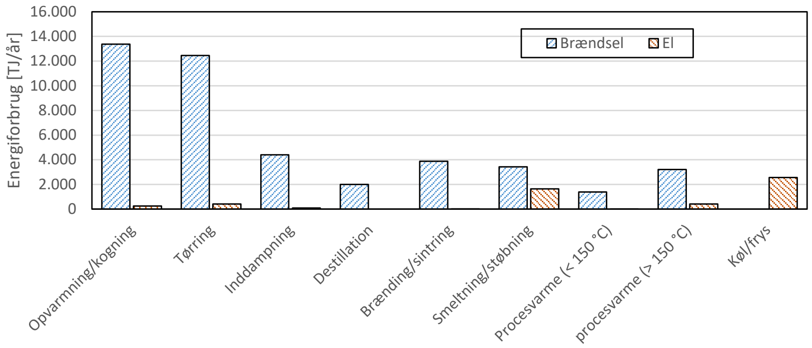


Figure 1.2: Energy use for unit operations in industry in Denmark in 2012 with share of electricity and fuel. Based on [19]

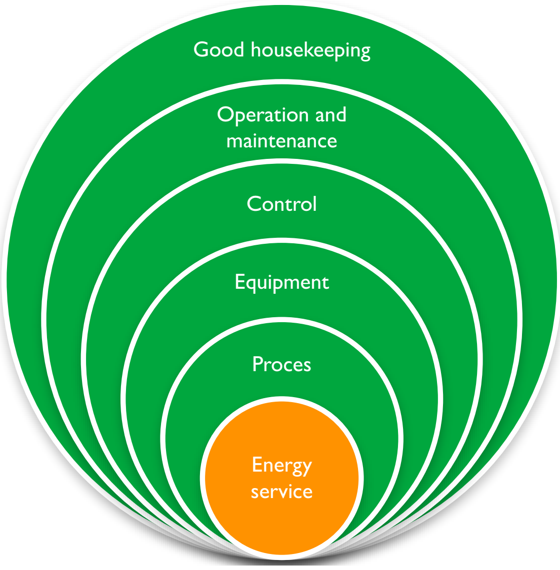


Figure 1.3: Onion diagram for illustration of energy use and efficiency potential in industry [7]

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.

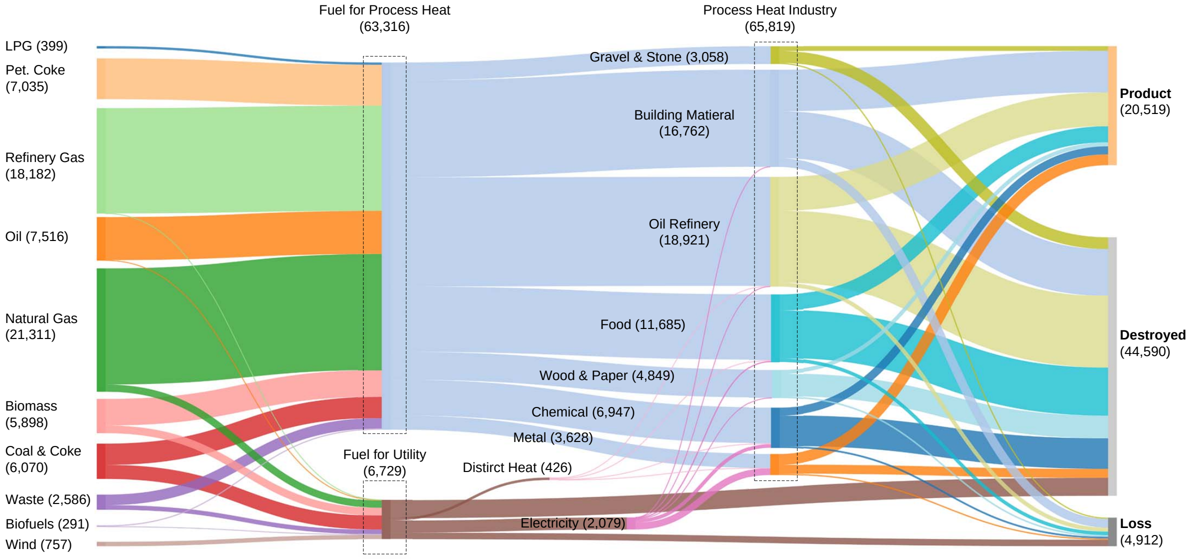


Figure 1.4: Exergy mapping of Danish industry energy consumption which documents the potential for energy savings through electrification [3]

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.

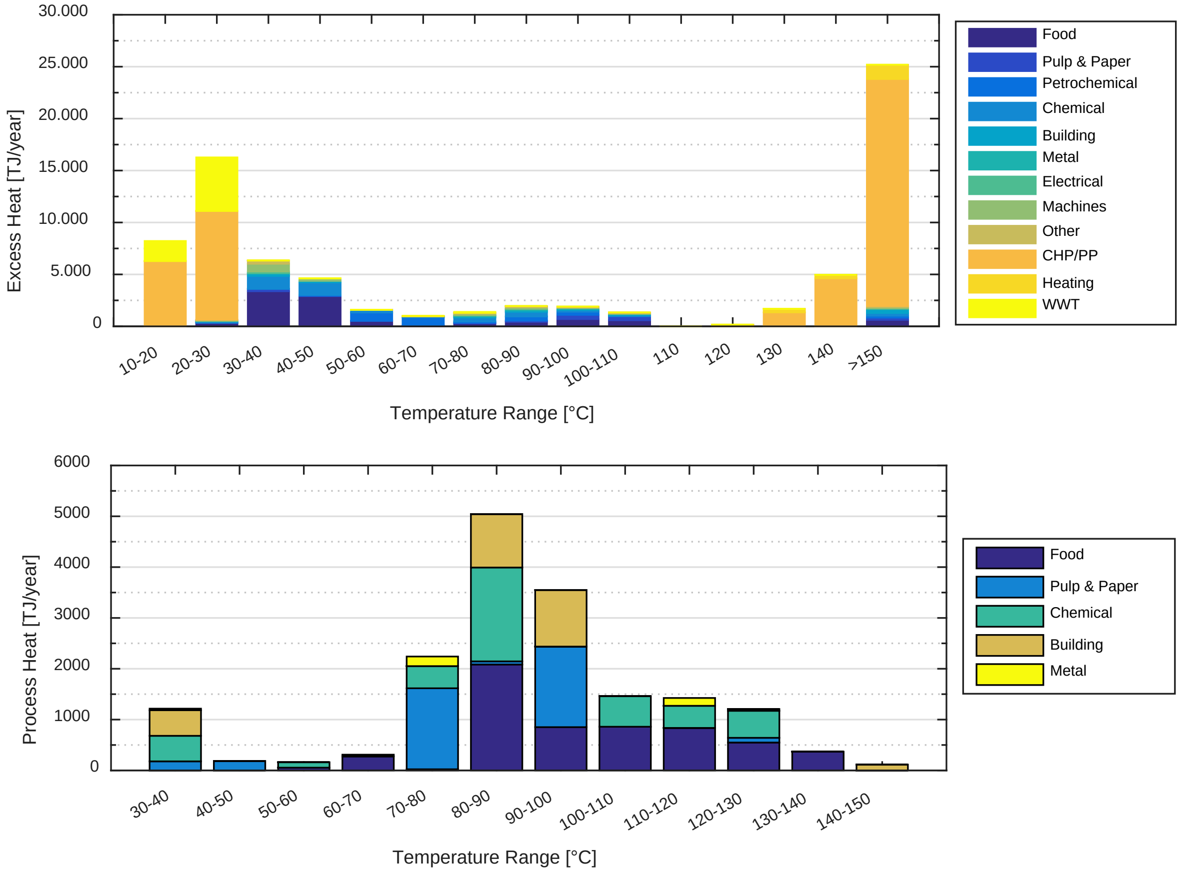


Figure 1.5: Temperature distribution of heat demand and heat surplus in Danish industry [4]

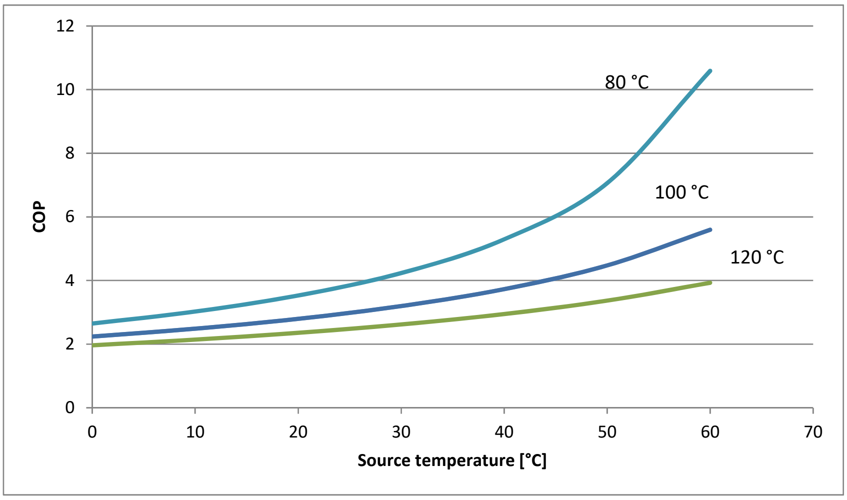


Figure 1.6: COP for heat pumps depending on temperature of heat source and heat demand

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.

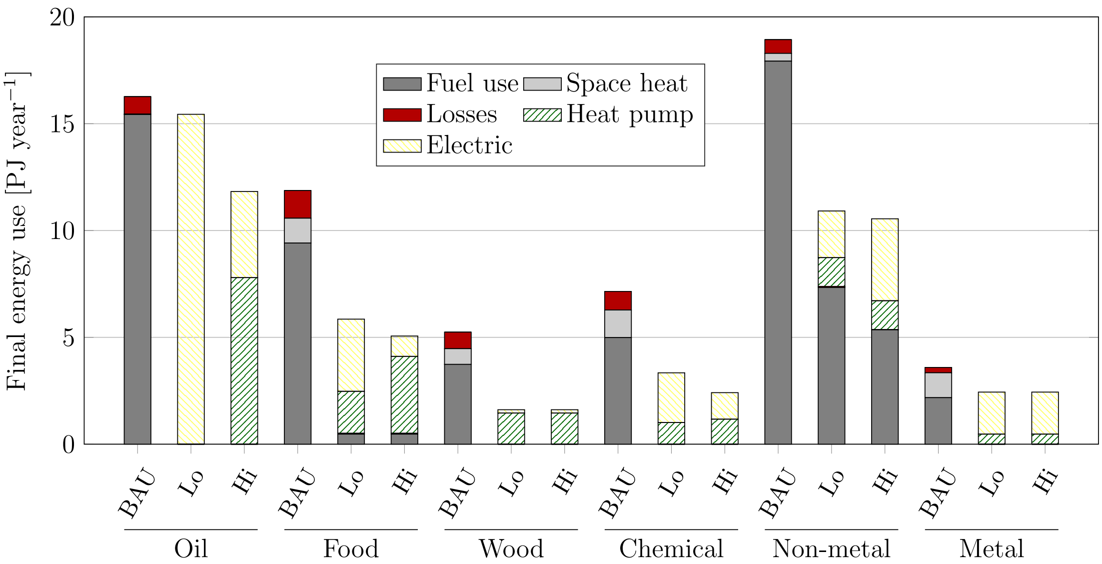


Figure 1.7: Potential for electrification of Danish industry sectors [6]

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

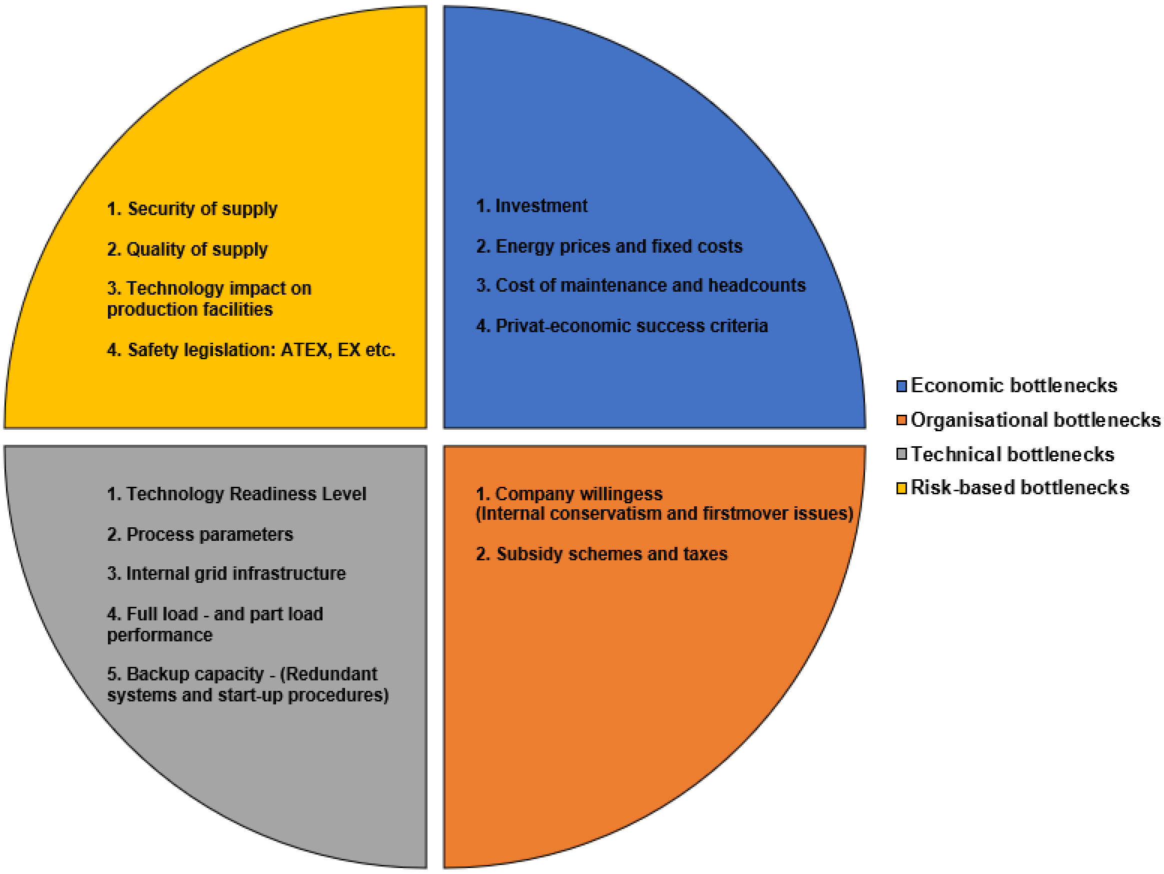


Figure 1.8: Bottlenecks for the electrification of industry A.4

(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

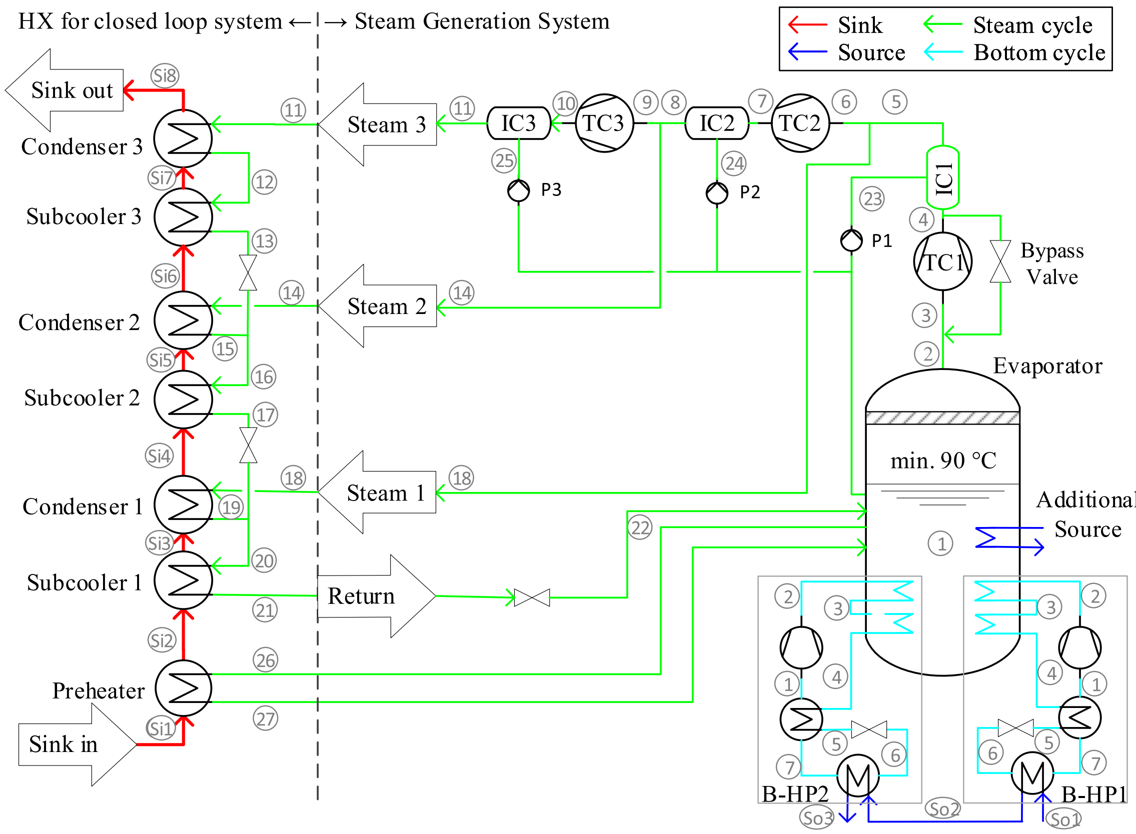


Figure 1.9: Cascade heat pump configuration for high temperature [20]

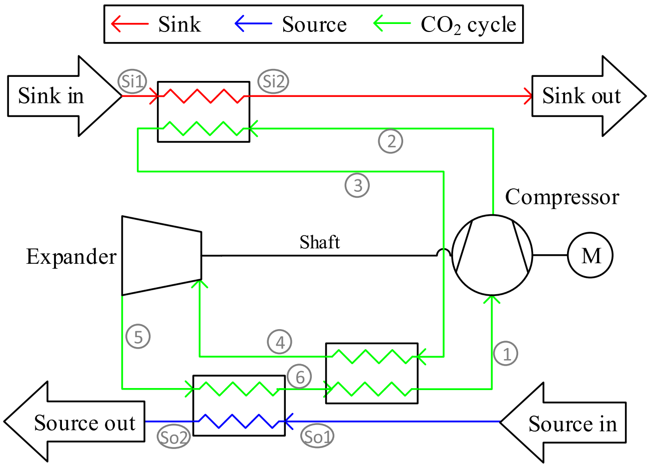


Figure 1.10: Brayton cycle heat pump configuration for high temperature [20]

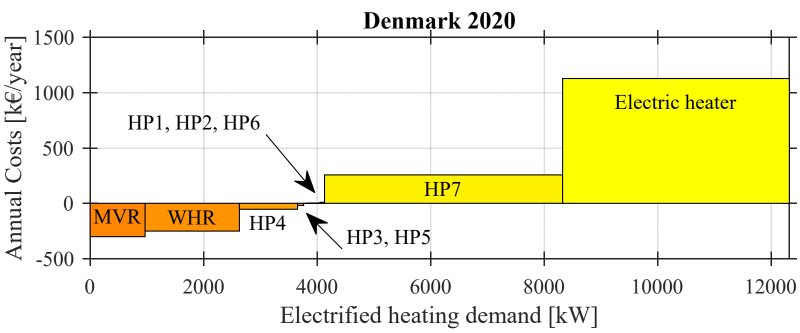


Figure 1.11: Feasibility of investment in electrification for milk powder production [5]

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.

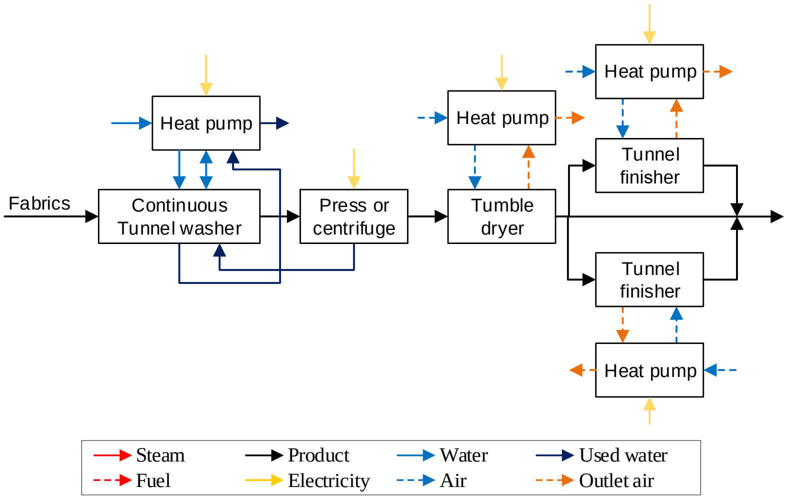


Figure 1.12: Electrified configuration of steam laundry [6]

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

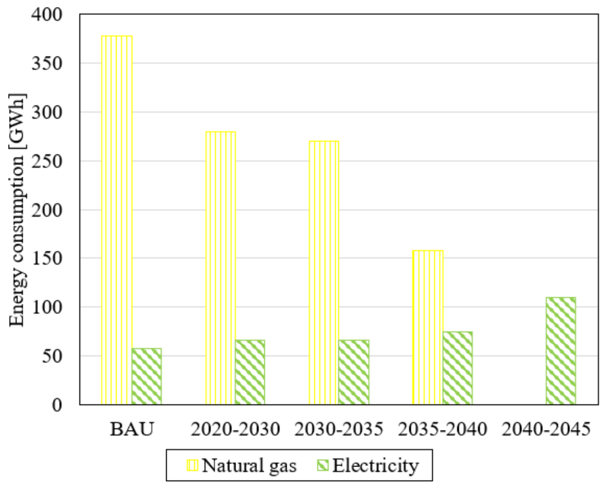


Figure 1.13: Electrification development for CP Kelco [17]

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

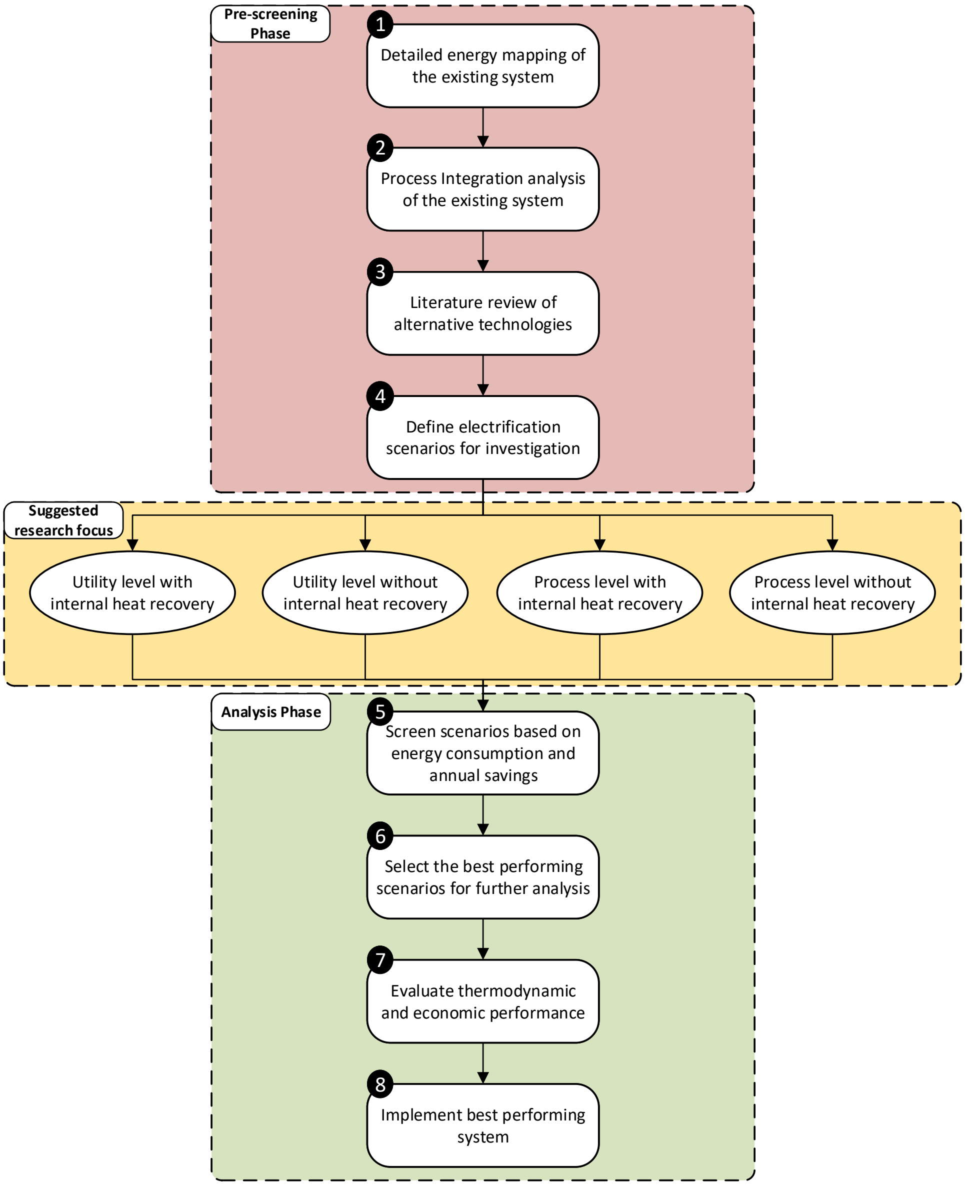


Figure 1.14: Procedure for energy efficiency and electrification of an industrial facility [11]

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.

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DTU Mechanical Engineering
Danmarks Tekniske Universitet
Nils Koppels Allé Bygning 403
DK-2800 Kgs. Lyngby, Denmark
Tlf. 4525 4131

www.mek.dtu.dk