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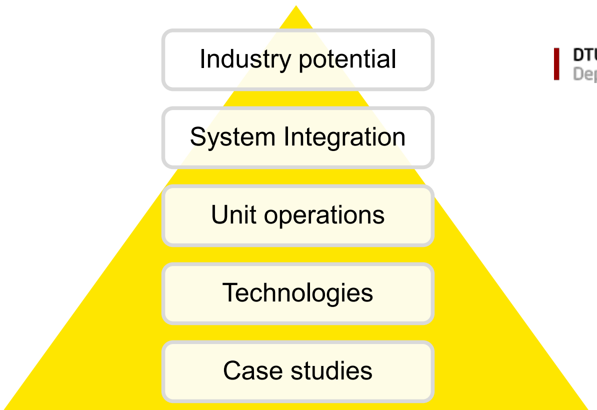
Electrification of processes and technologies for Danish Industry

Elforsk project 350-038

Appendix A



DTU Mechanical Engineering
Department of Mechanical Engineering

viegand maagøe
energy people

DANISH TECHNOLOGICAL INSTITUTE

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SAN
Electro Heat

ELFORSK

Labotek

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

Appendix A
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By
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Abstract

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

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

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

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

the industry and for the individual cases.

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

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

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

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

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

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

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

Resumé

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

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

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

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

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

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

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

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

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

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

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

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

A Potentials for the electrification of industrial processes in Denmark

Potentials for the electrification of industrial processes in Denmark

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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 ($< 100\,°C$) is primarily used in the food industry, while high temperature heat ($> 500\,°C$) 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.

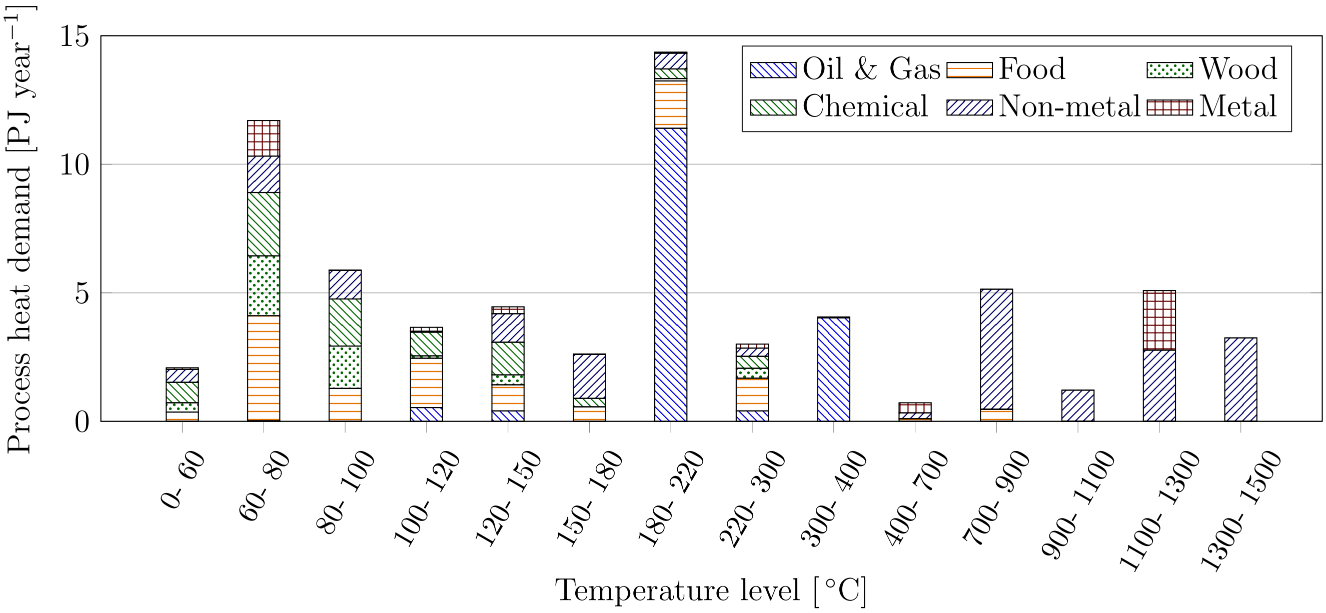


Figure 1: Industrial process heat demand by temperature level and sector in 2012. Based on data from [20, 21]

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

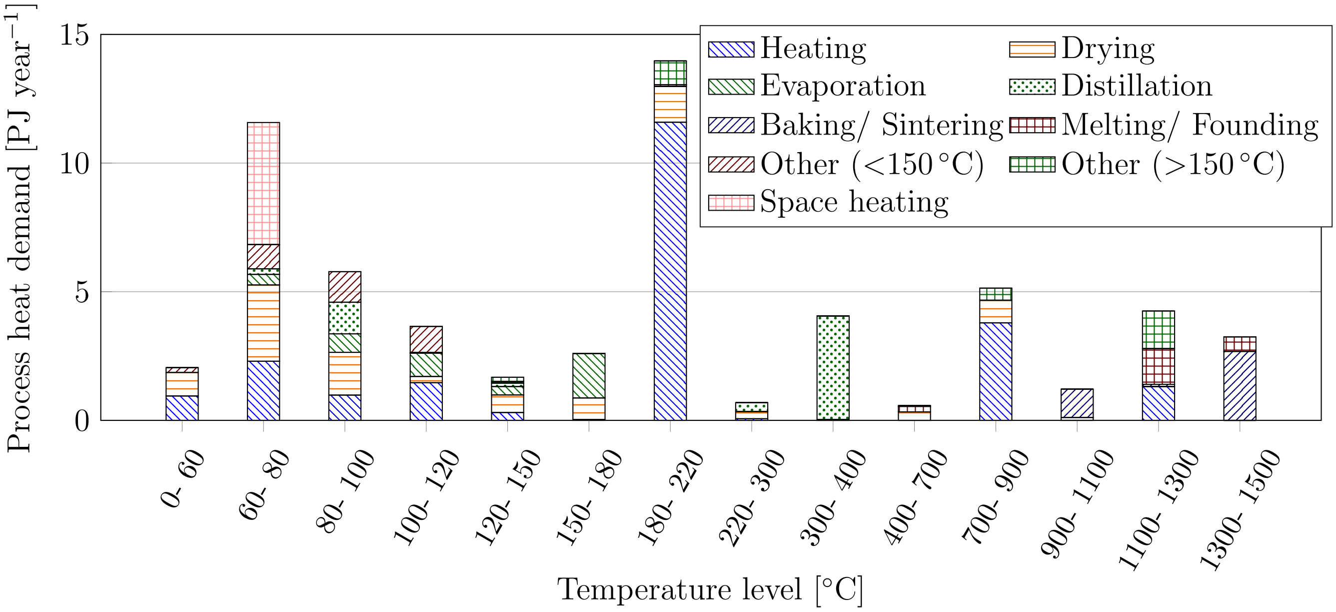


Figure 2: Industrial process heat demand by temperature level and process in 2012. Based on data from [20, 21]

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

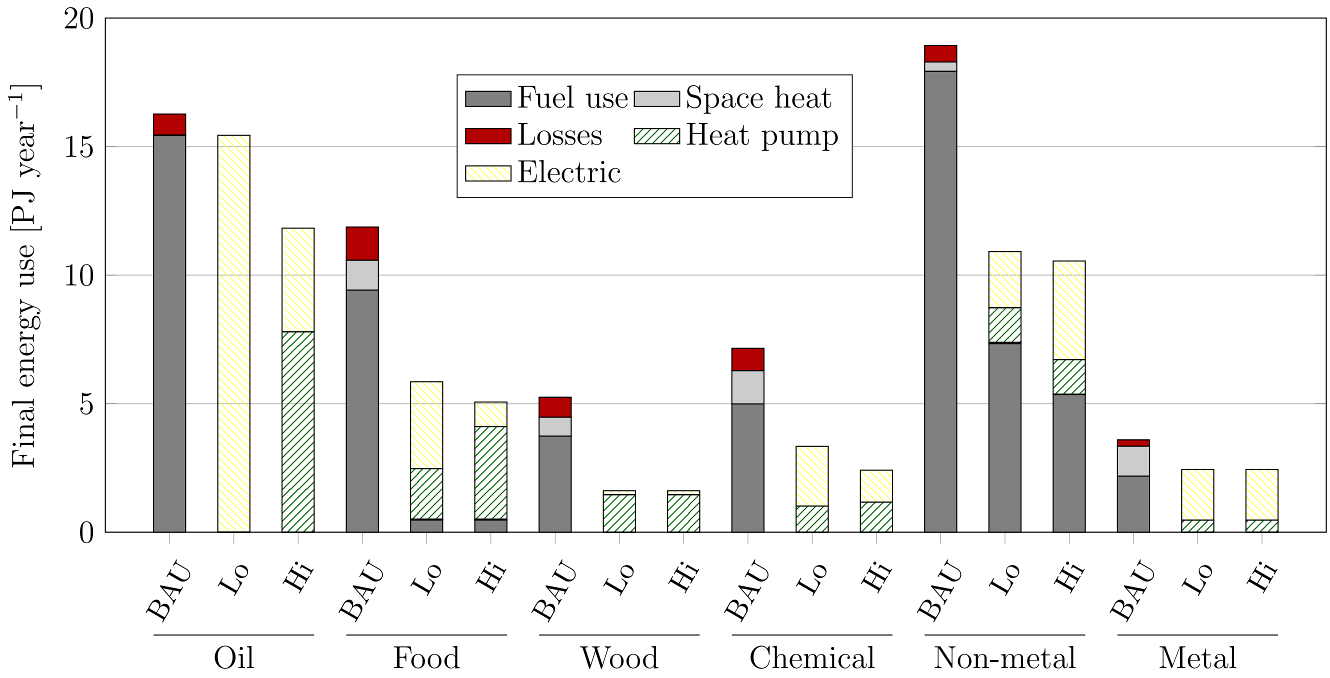
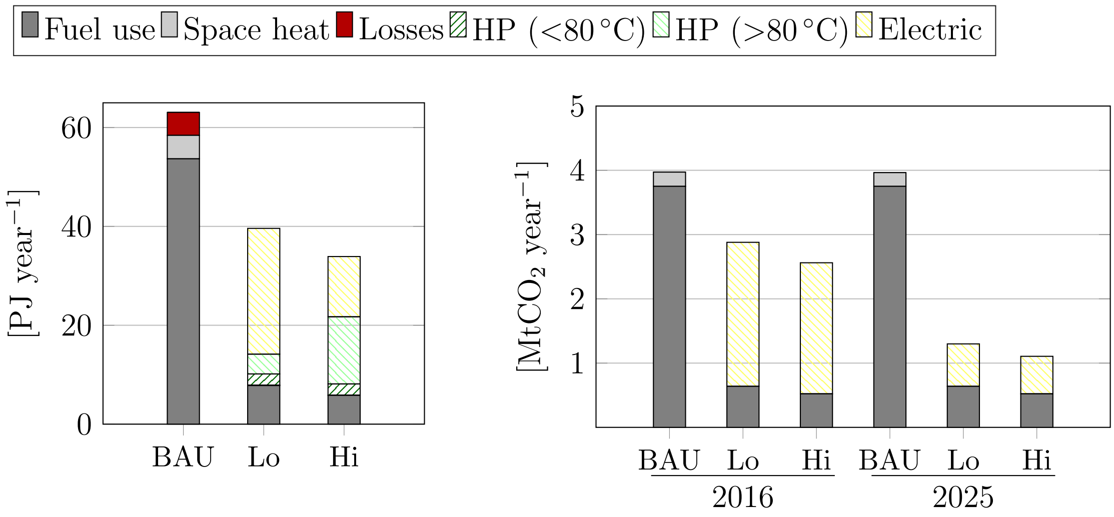


Figure 3: Final energy use for heating in the main industry sectors in Denmark for different scenarios. "BAU" desribes the current system, "Lo" and "Hi" the electrified systems.

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

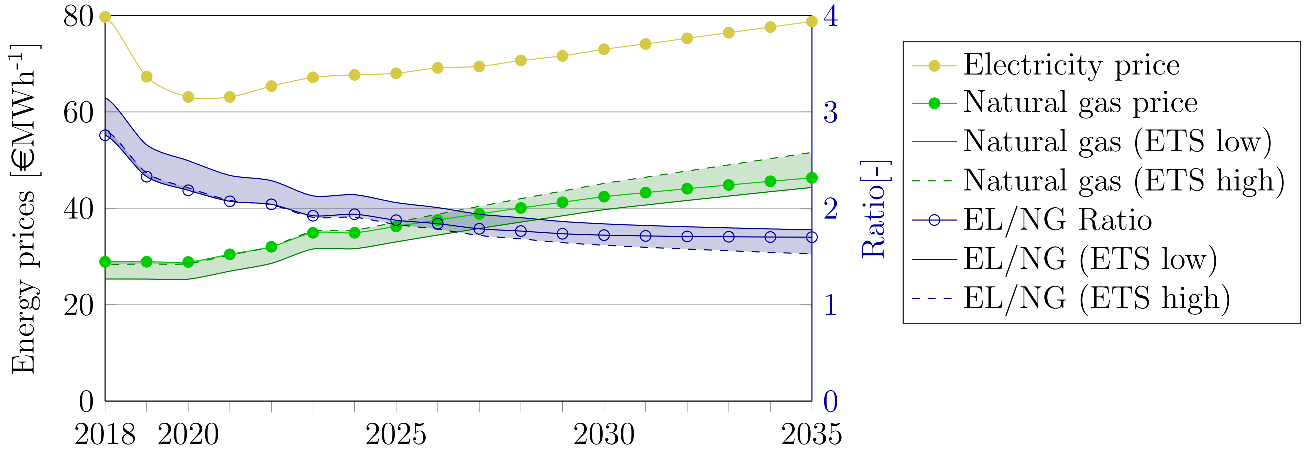
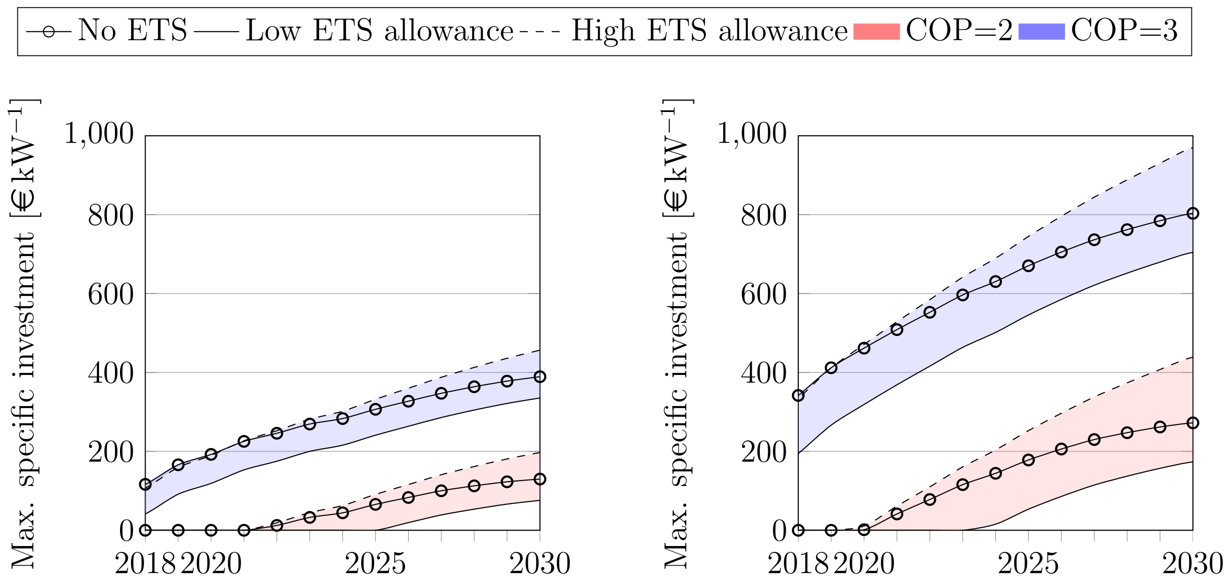


Figure 5: Development of energy prices for industrial process heat in Denmark until 2035 and the ratio between Electricity and natural gas. The addition of (ETS) indicates the inclusion of low and high costs for CO_2 allowances.



(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

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 processes and technologies in the Danish industry".

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

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Elektrificering af processer og teknologier i dansk industri

Potentials for the electrification of industrial processes in Denmark

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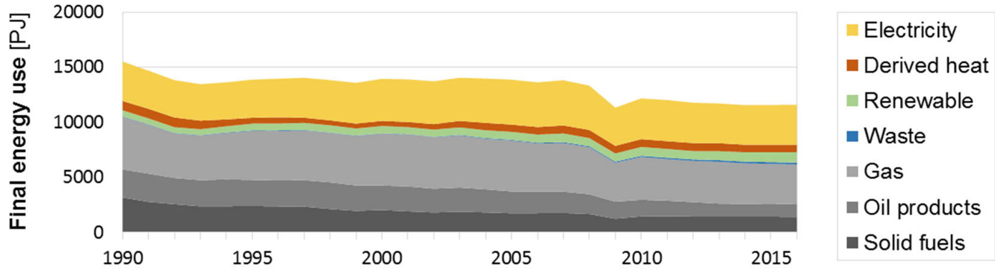
Introduction

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)

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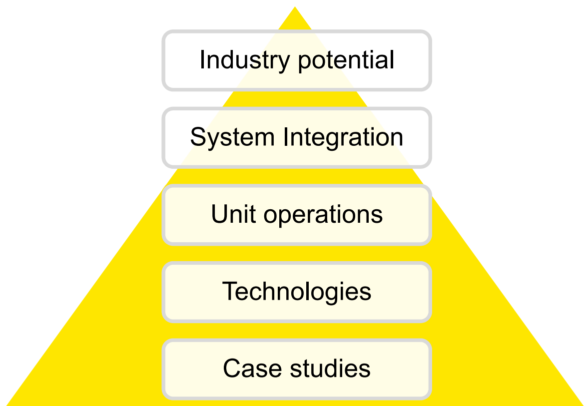
Introduction

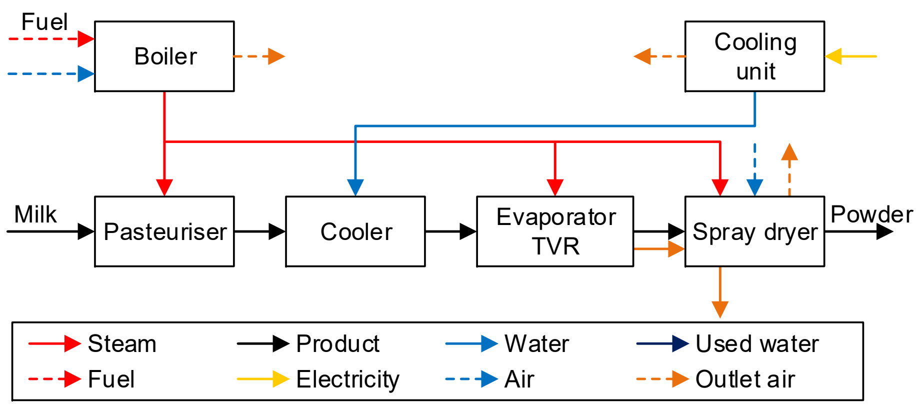
Objective
- Reduce energy use in thermal processes
- Electrification options and technologies
- **Potential for electrification in industry**
- Challenges and boundary conditions for electrification

Approach



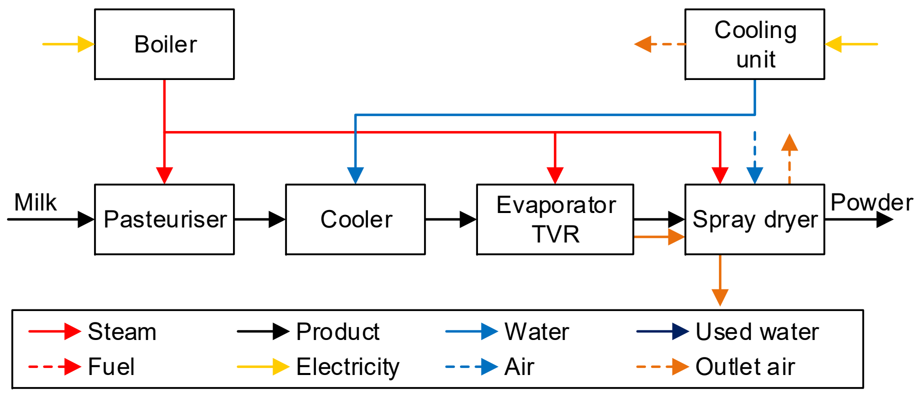
Electrification of industrial processes

- Electrofuels



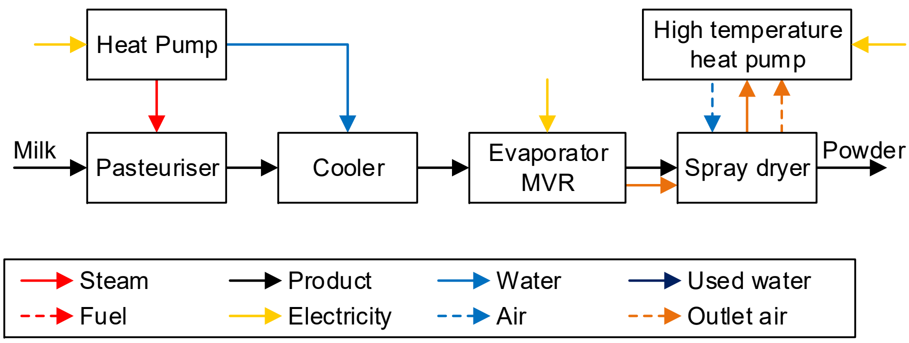
Electrification of industrial processes

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



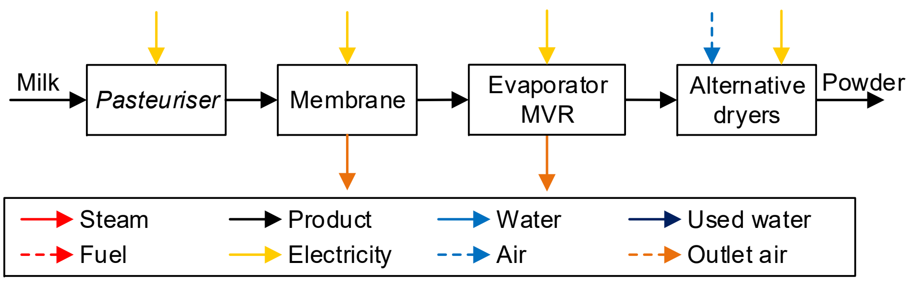
Electrification of industrial processes

- 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

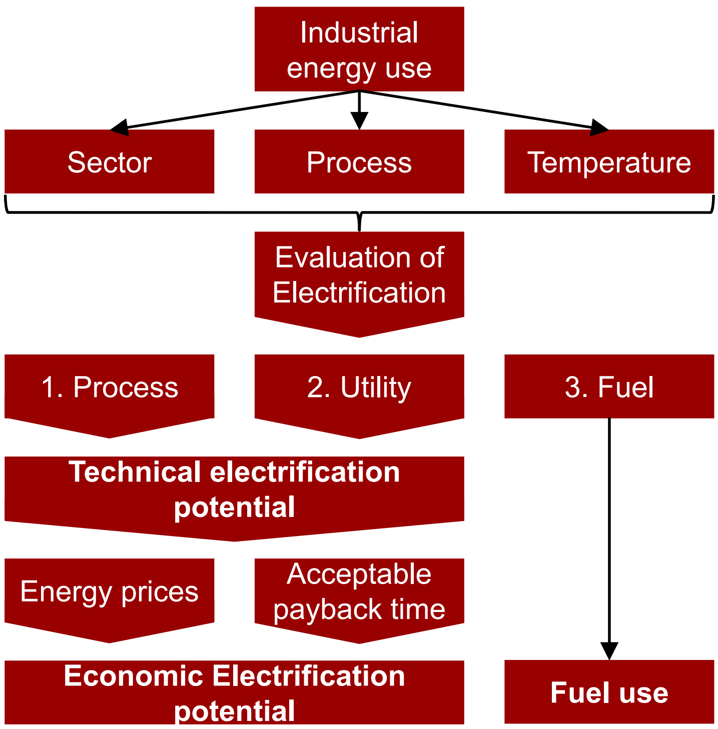
- Power to fuel
- Power to heat (central)
- Power to heat (process)
- Power to Y

↓ Energy use

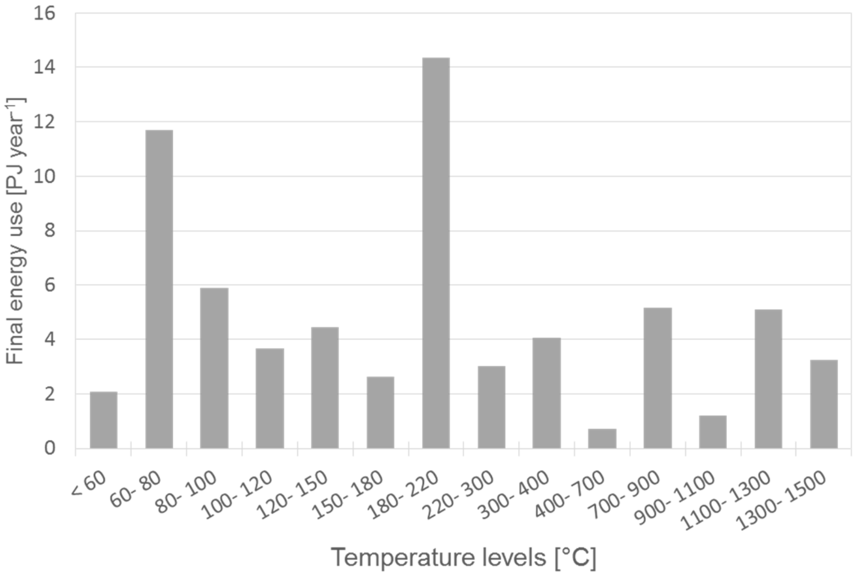
↑ Changes in production

↑ Required Innovation/ R&D potential

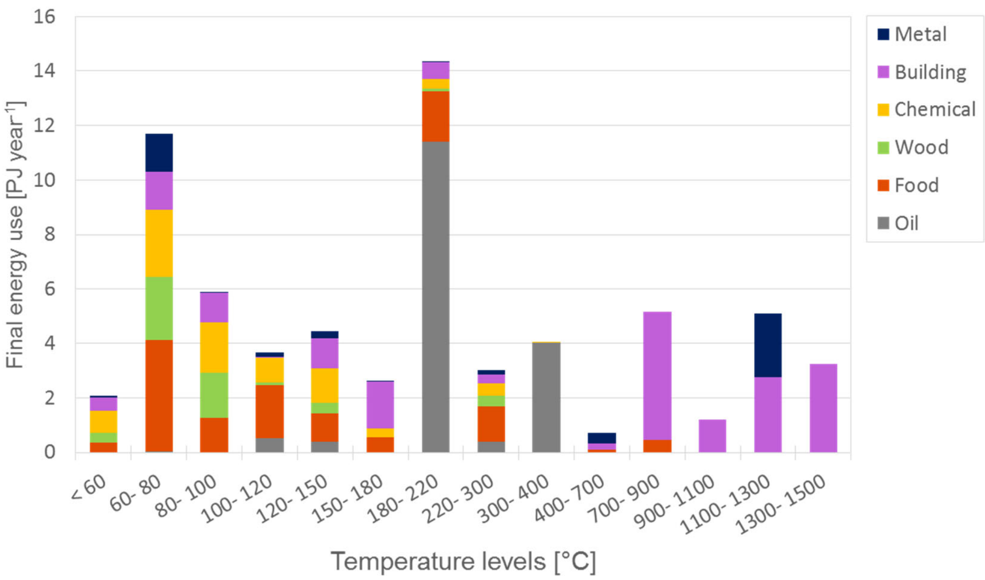
Approach
Establishing electrification potential



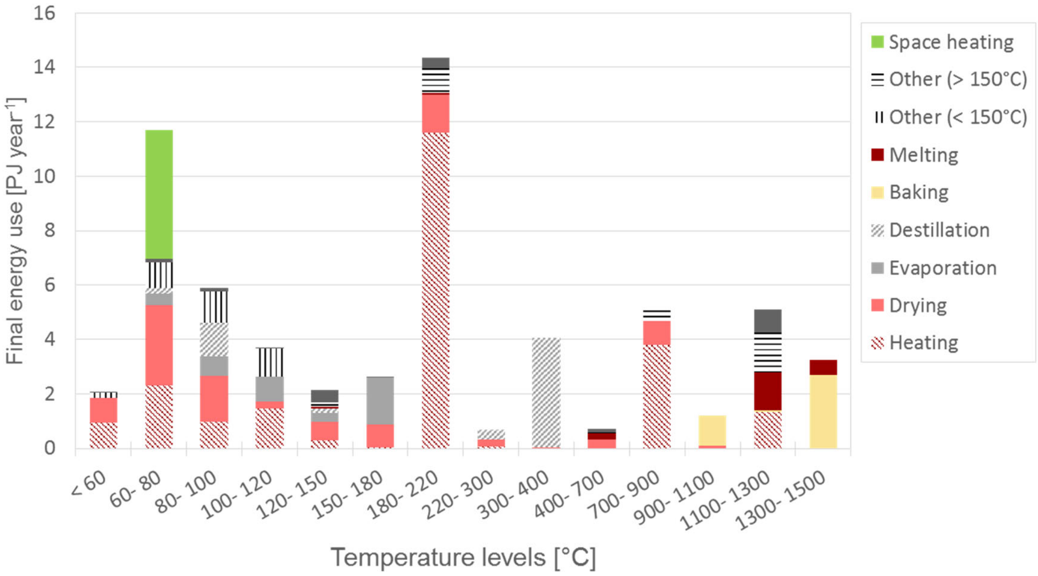
Industrial energy use in Denmark



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

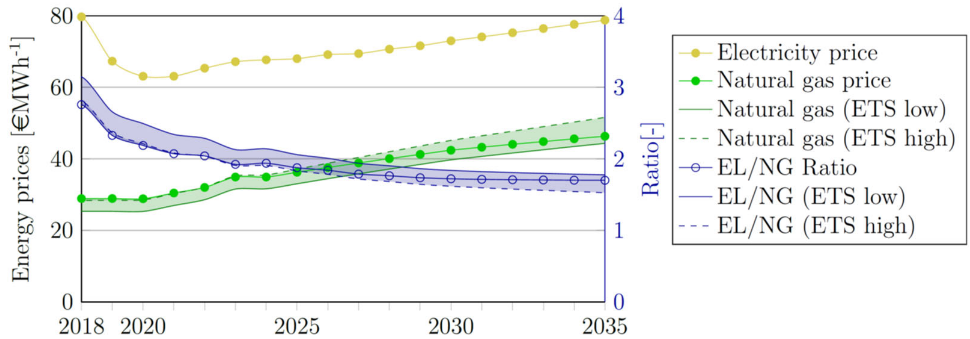
- Brick production -> Microwave assisted kiln
- Cement production -> Clinker heating
- Drying of metal paints -> IR drying
- Melting e.g. Aluminium -> Induction furnaces

Scenario and economic analysis

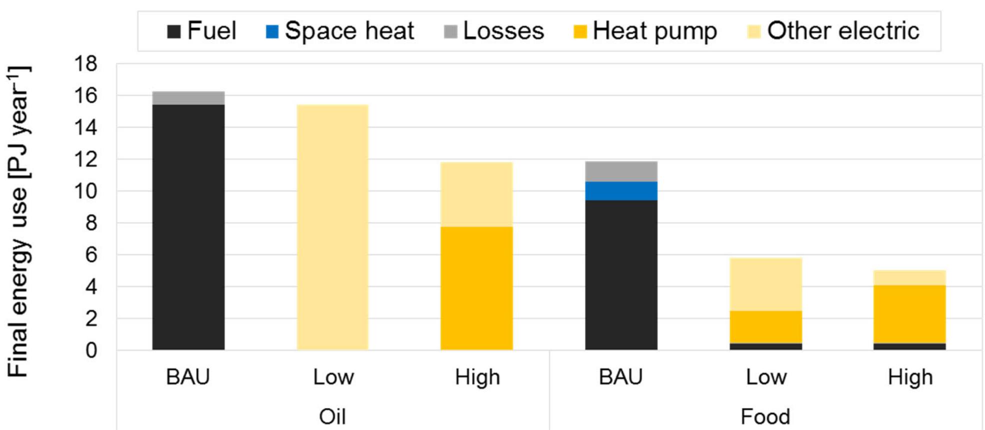
Technology scenarios:

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

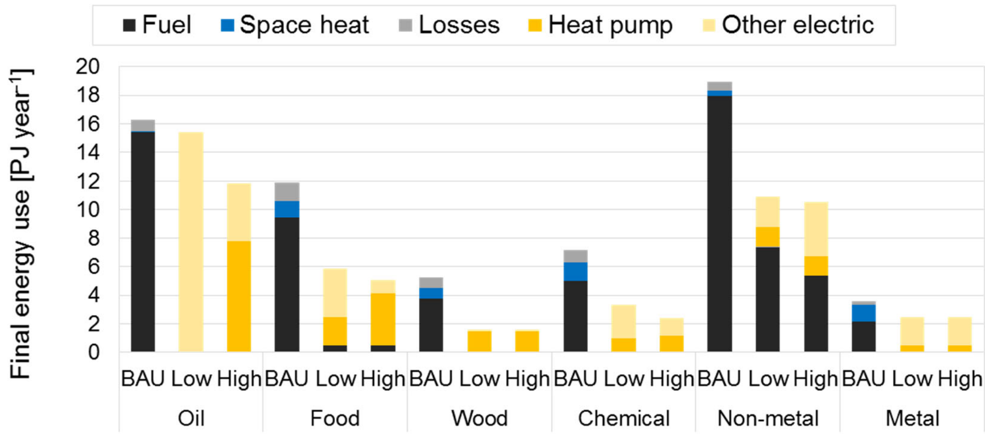
Energy price scenarios:



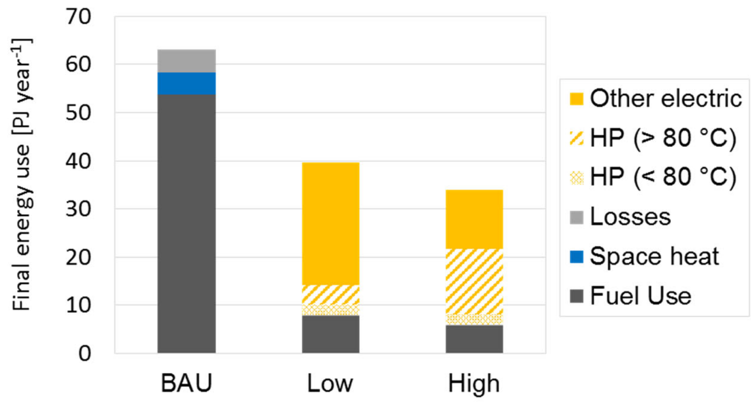
Electrification potential



Electrification potential

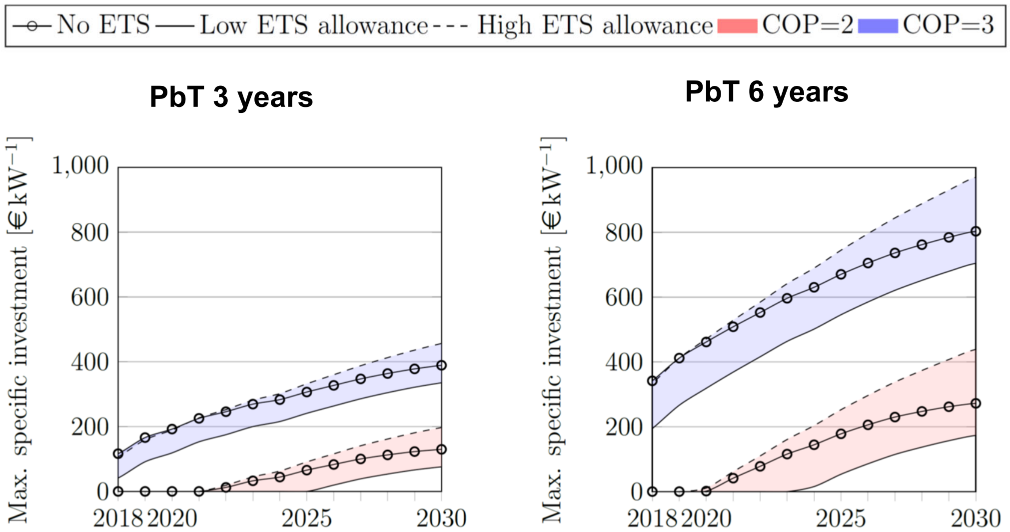


Electrification potential

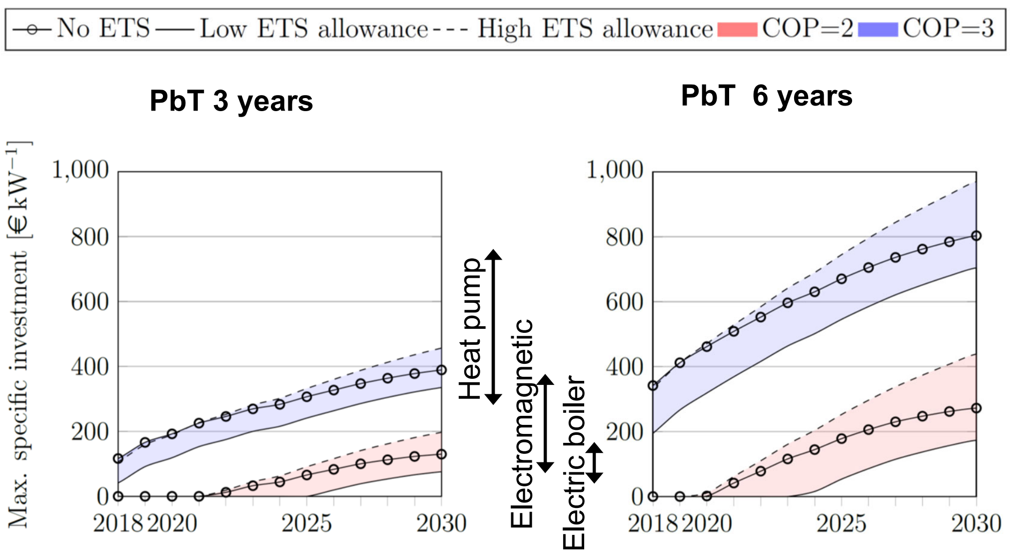


- CO_2-emission reduction from electrification
  - 2016: 28% to 36%
  - 2025: 68% to 72%

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!

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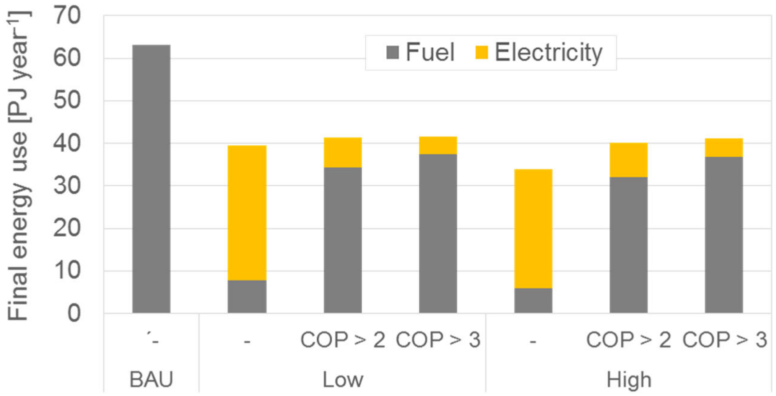
DTU

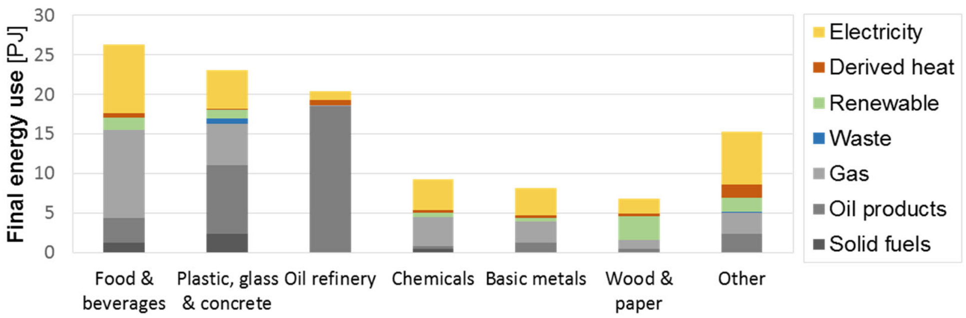
Economic electrification potential



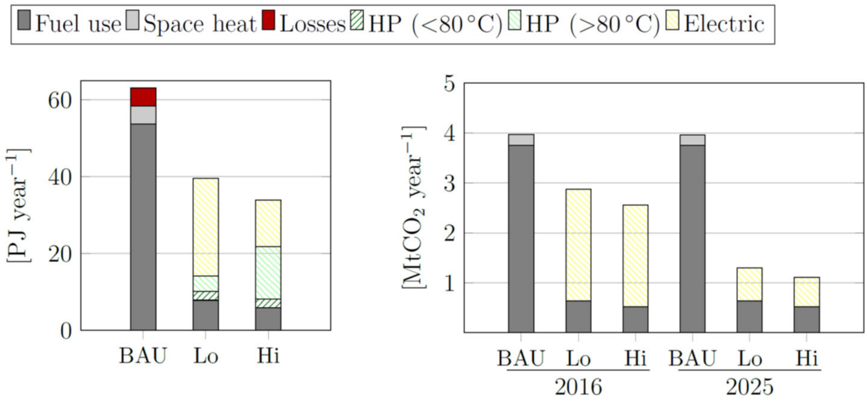
- Final energy use almost constant
- Share of electricity decreases substantially

DTU

Energy use by source and sector in DK



Results

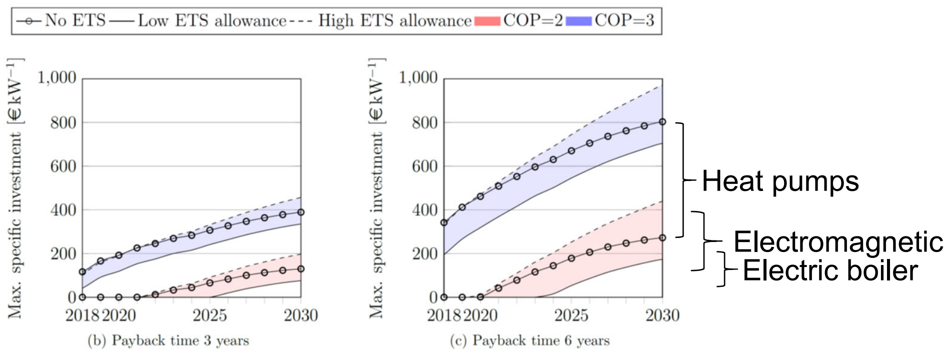


(a) Final energy use (b) CO_2-emissions

Technology Overview

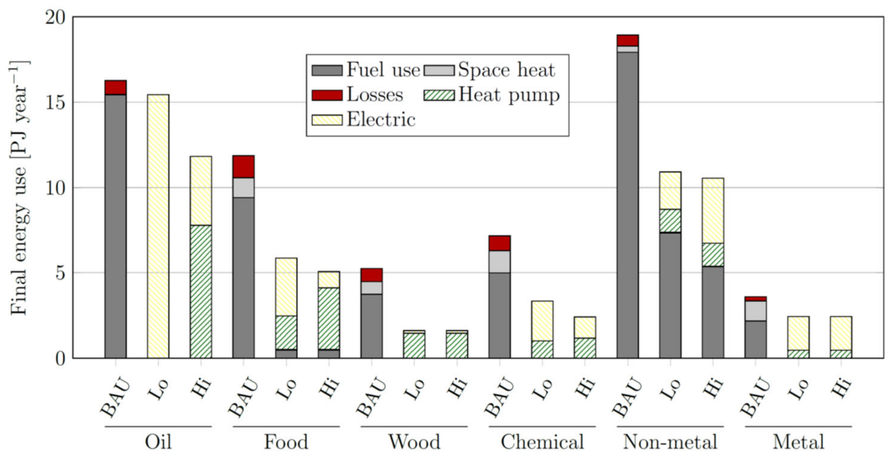
Process	Technology	Availability	Output
Process heat (steam, water)	Heat pump	High	
	HTHP	Medium	
	Electric boiler	High	
	Electrode Boiler	High	
	Vapour recompression	High	
-Drying	Electromagnetic	Medium	+
	Impulse drying	Low	
	Impingement drying	Low	
-Sterilisation/ pasteurisation	Electromagnetic	Medium	+
	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

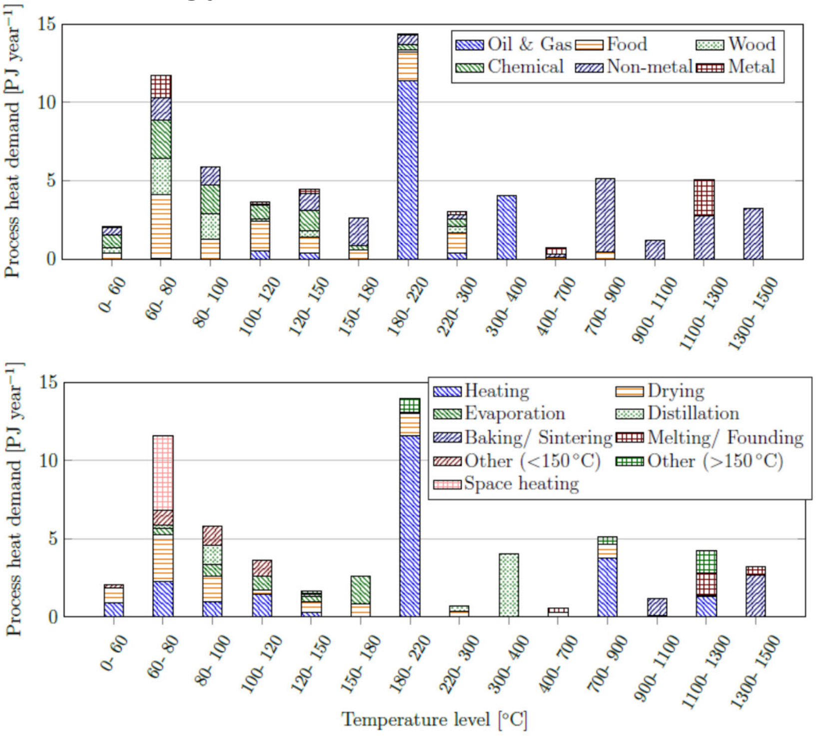


	Min. COP	Fuel Use [PJ]	Electricity Use [PJ]	Fuel use reduction
BAU	-	63.1	-	-
Hi	-	5.9	28.0	91%
	2	32.0	8.1	49%
	3	36.8	4.3	42%
Lo	-	7.9	31.7	87%
	2	34.3	7.1	46%
	3	37.4	4.1	41%

Results



Method
Industrial energy use in Denmark



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

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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.

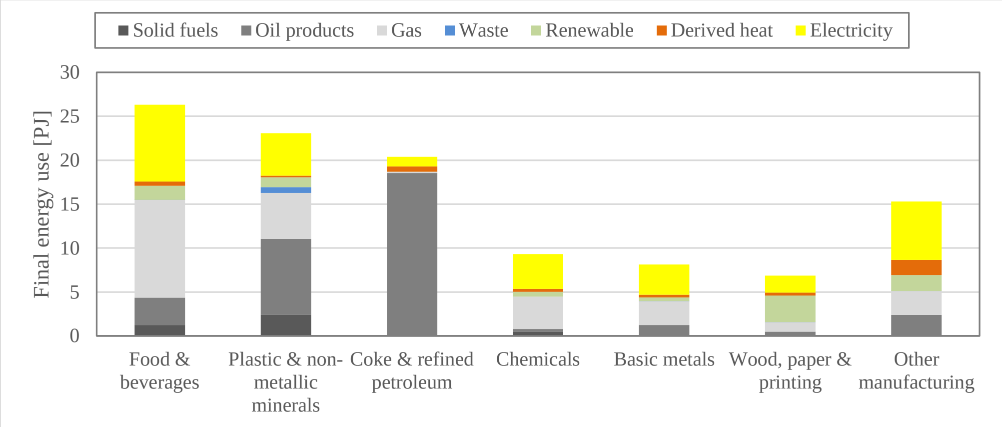

Figure 1: Total final energy use in the Danish industry by industrial sector and energy carrier in 2016 (Denmark Statistics, 2017)

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

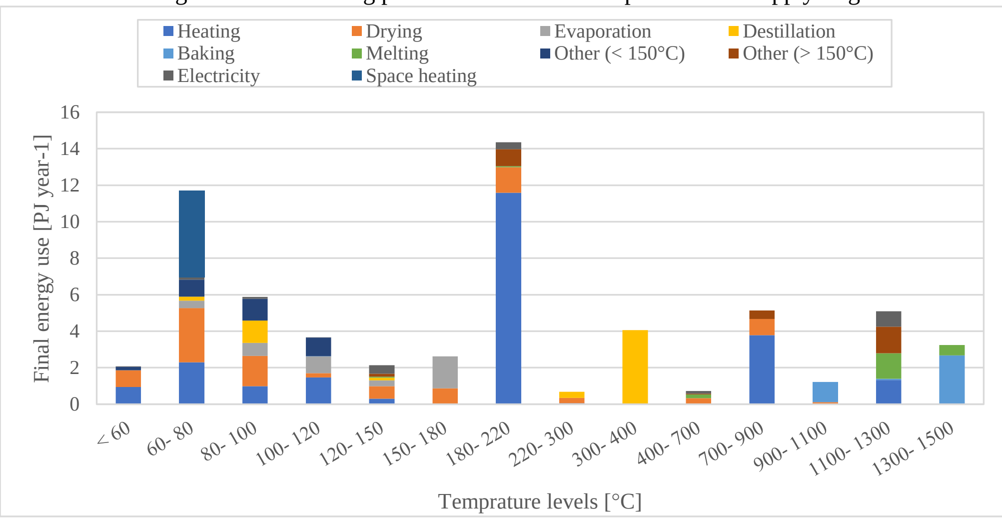

Figure 2: Final energy use of the 21 most energy intense manufacturing industries by temperature and process (Bühler et al., 2016a; Sørensen et al., 2015).

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.

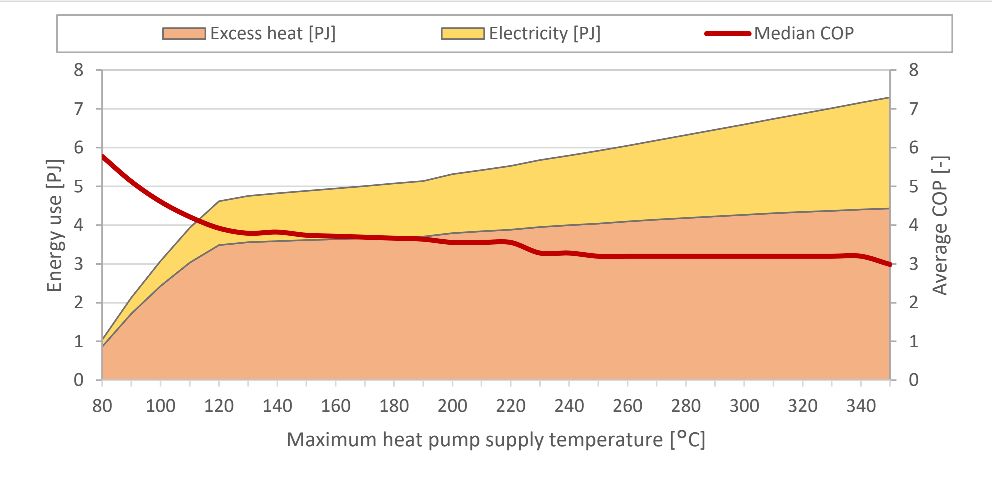

Figure 3: Utilisation potential of excess heat with heat pumps and average COP in the Danish manufacturing industry assuming the heat pump sink is heated from the excess heat temperature to the maximum supply temperature.

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.

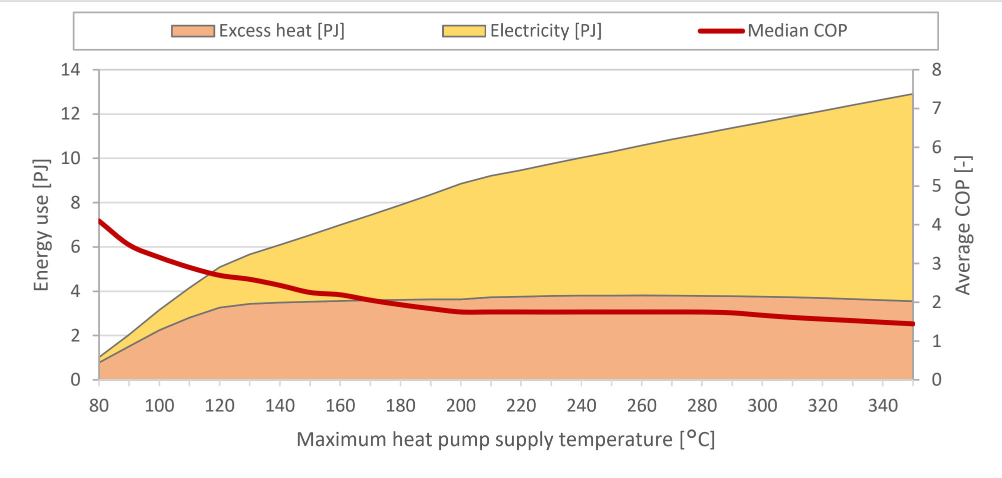

Figure 4: Utilisation potential of excess heat with heat pumps and average COP in the Danish manufacturing industry assuming all heat is supplied at the maximum heat pump supply temperature.

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.

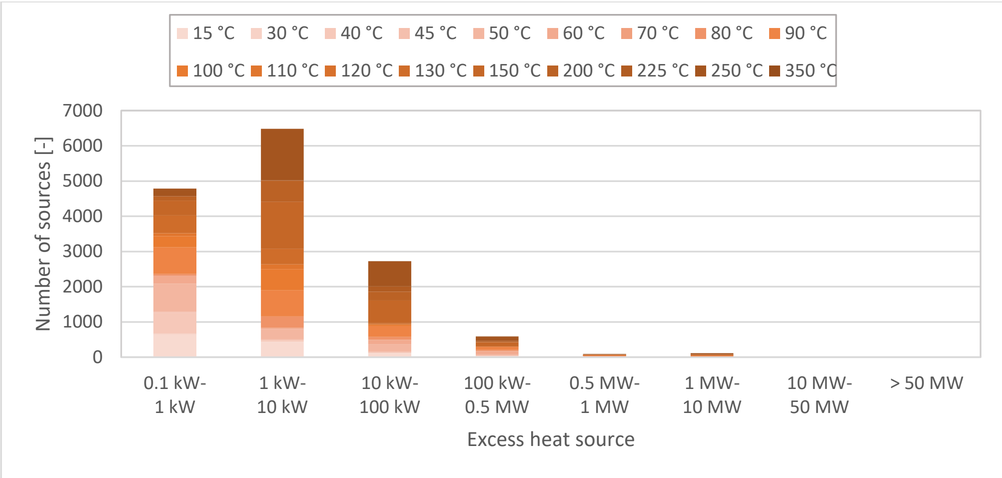

Figure 5: Distribution of excess heat sources from thermal processes in the Danish manufacturing industry (number of sources).

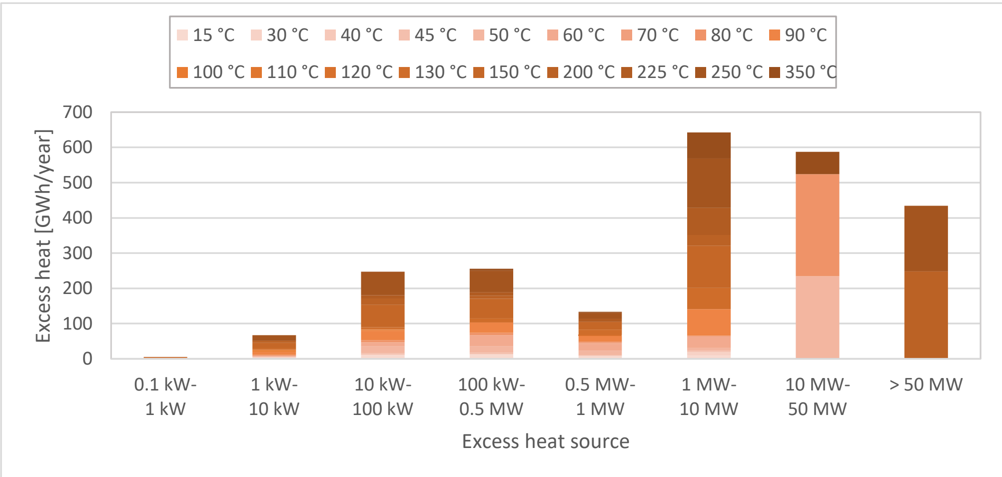

Figure 6: Distribution of excess heat sources from thermal processes in the Danish manufacturing industry (excess heat potential).

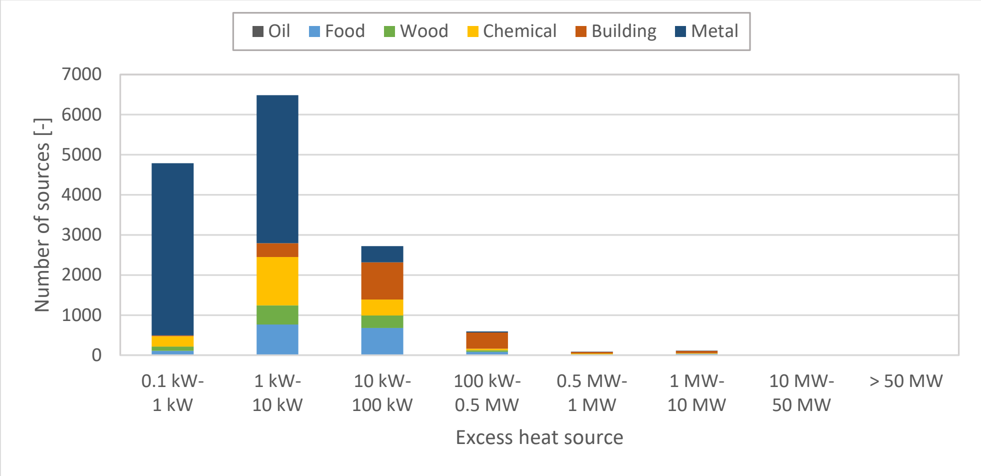

Figure 7: Distribution of excess heat sources from thermal processes in the Danish manufacturing industry (number of sources).

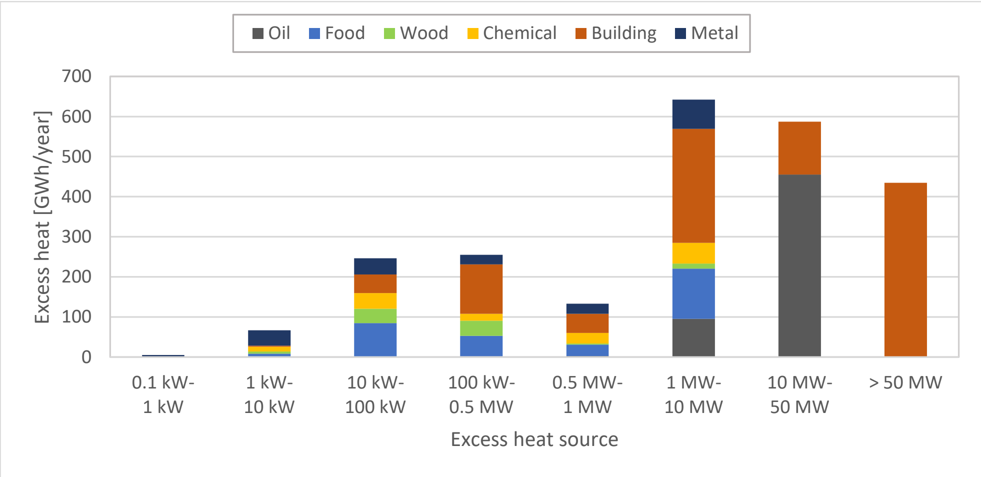

Figure 8: Distribution of excess heat sources from thermal process in the Danish manufacturing industry.

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.

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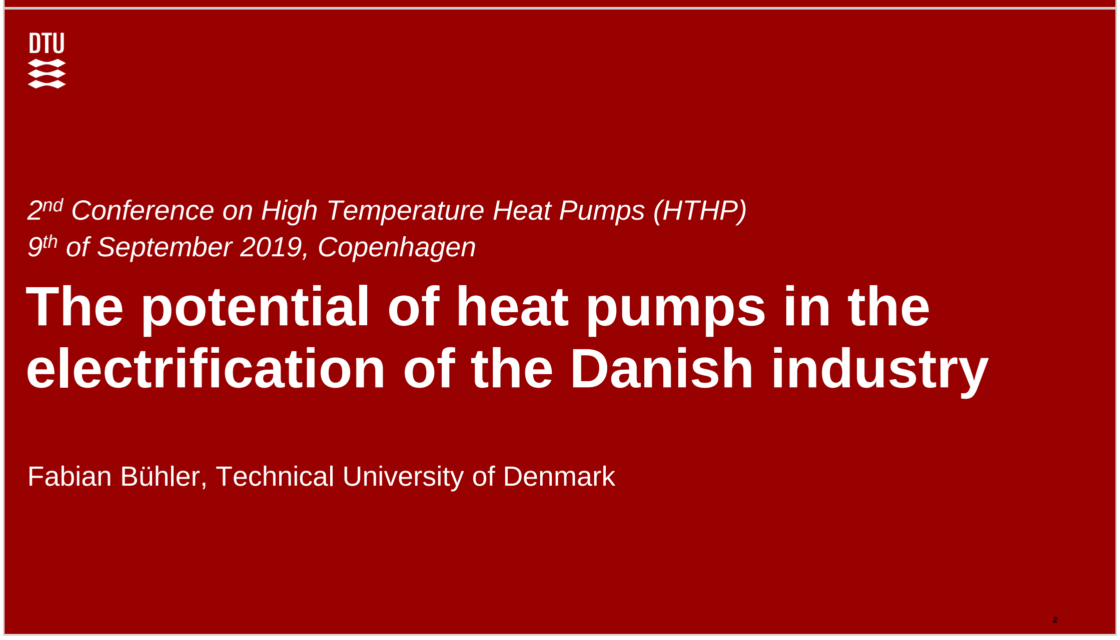
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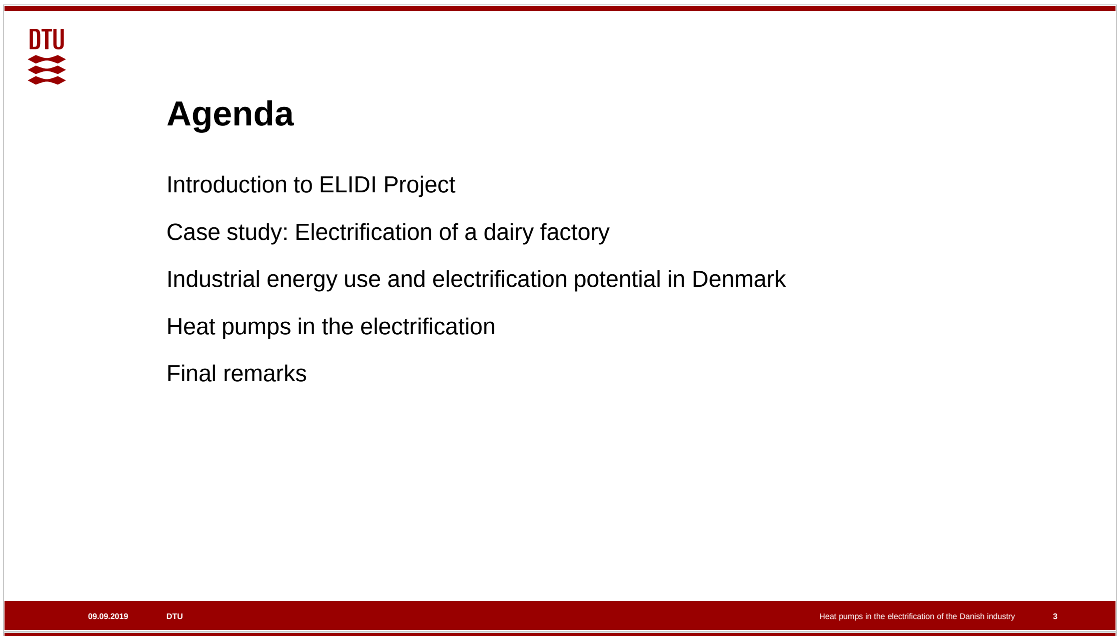
2nd Conference on High Temperature Heat Pumps (HTHP)
9th of September 2019, Copenhagen
The potential of heat pumps in the electrification of the Danish industry
Fabian Bühler, Technical University of Denmark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Agenda
Introduction to ELIDI Project
Case study: Electrification of a dairy factory
Industrial energy use and electrification potential in Denmark
Heat pumps in the electrification
Final remarks
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Heat pumps in the electrification of the Danish industry
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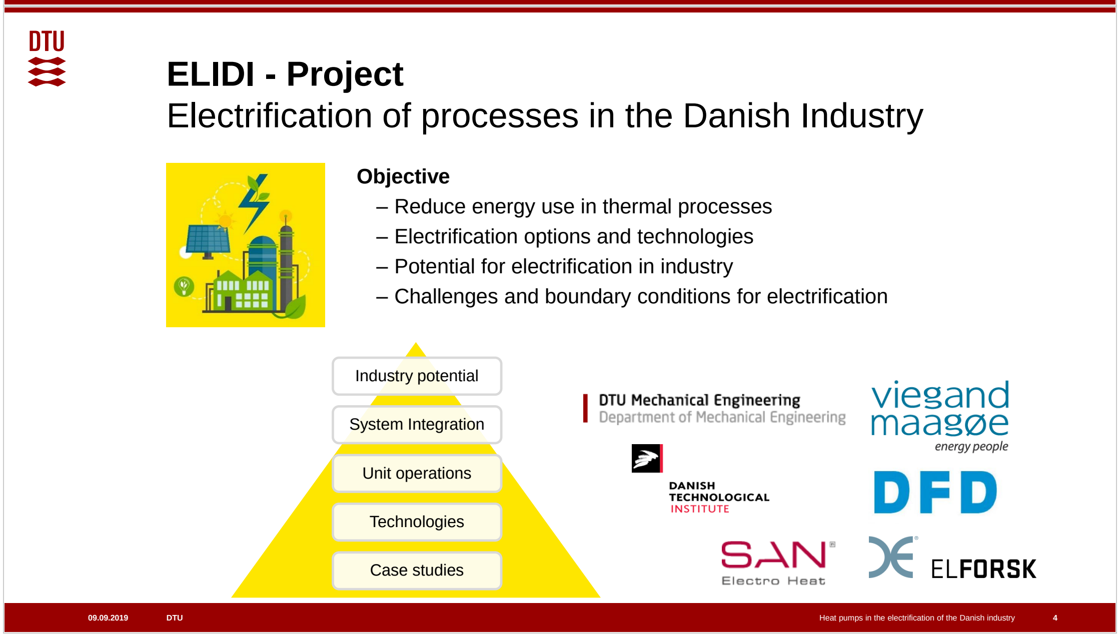
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ELIDI - Project
Electrification of processes in the Danish Industry
Objective
– Reduce energy use in thermal processes
– Electrification options and technologies
– Potential for electrification in industry
– Challenges and boundary conditions for electrification
Industry potential
System Integration
Unit operations
Technologies
Case studies
DTU Mechanical Engineering
Department of Mechanical Engineering
viegand maagøe
energy people
DANISH TECHNOLOGICAL INSTITUTE
DFD
SAN
Electro Heat
ELFORSK
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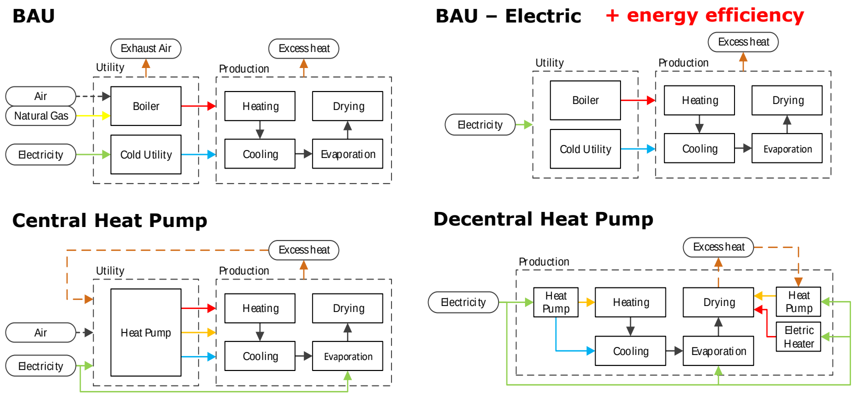
Electrification of dairy factory (milk powder)

Possible strategies



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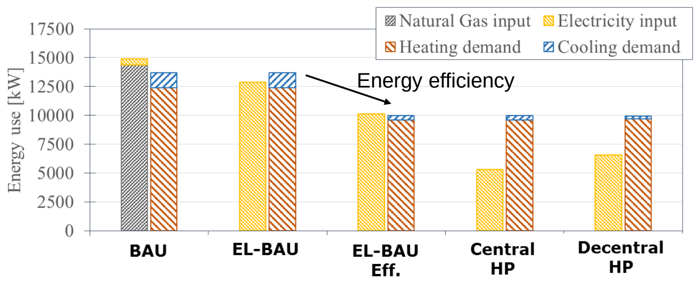
Electrification – Dairy factory

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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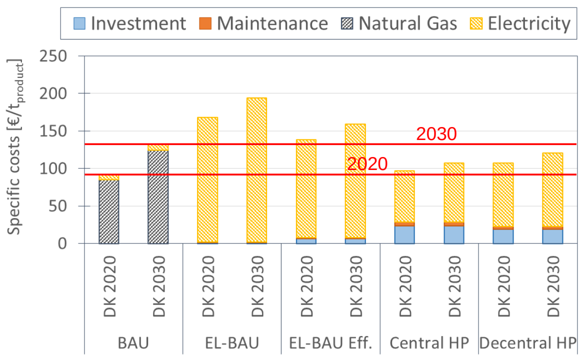
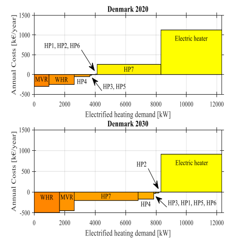
Electrification – Dairy factory
Economic analysis



Simple payback time

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



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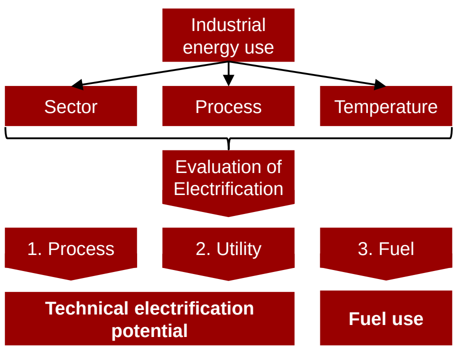
Electrification potential in Denmark
Approach



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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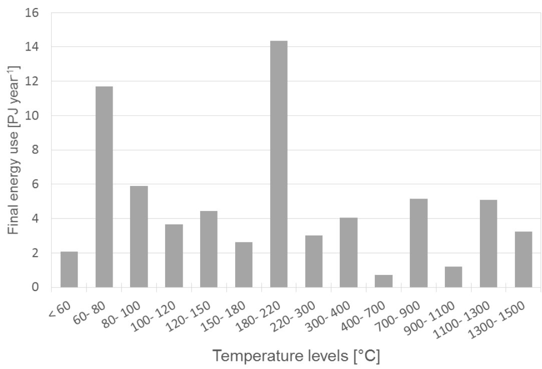
Industrial energy use in Denmark



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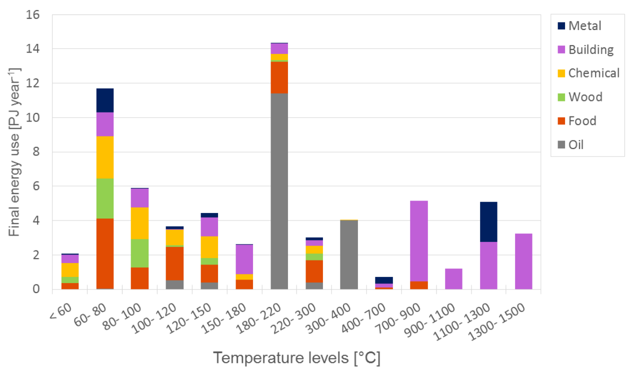
Industrial energy use in Denmark



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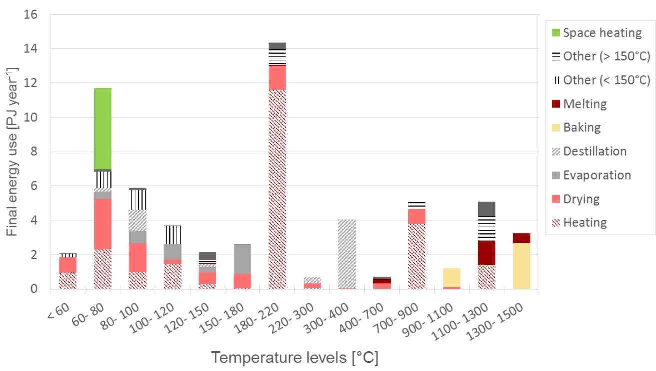
Industrial energy use in Denmark



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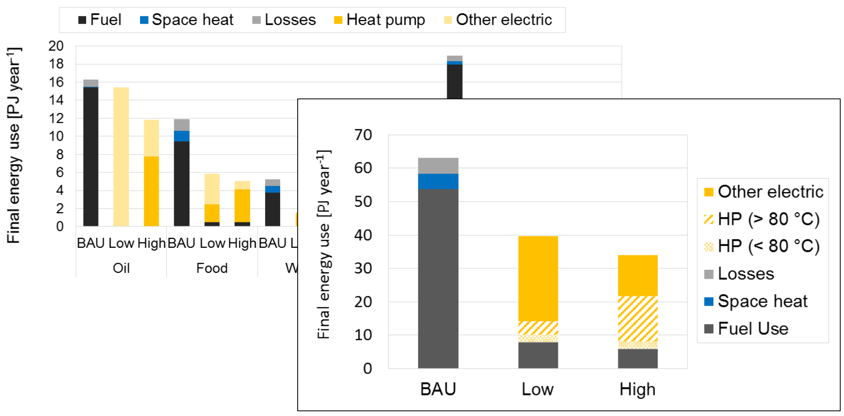
Electrification potential in Denmark



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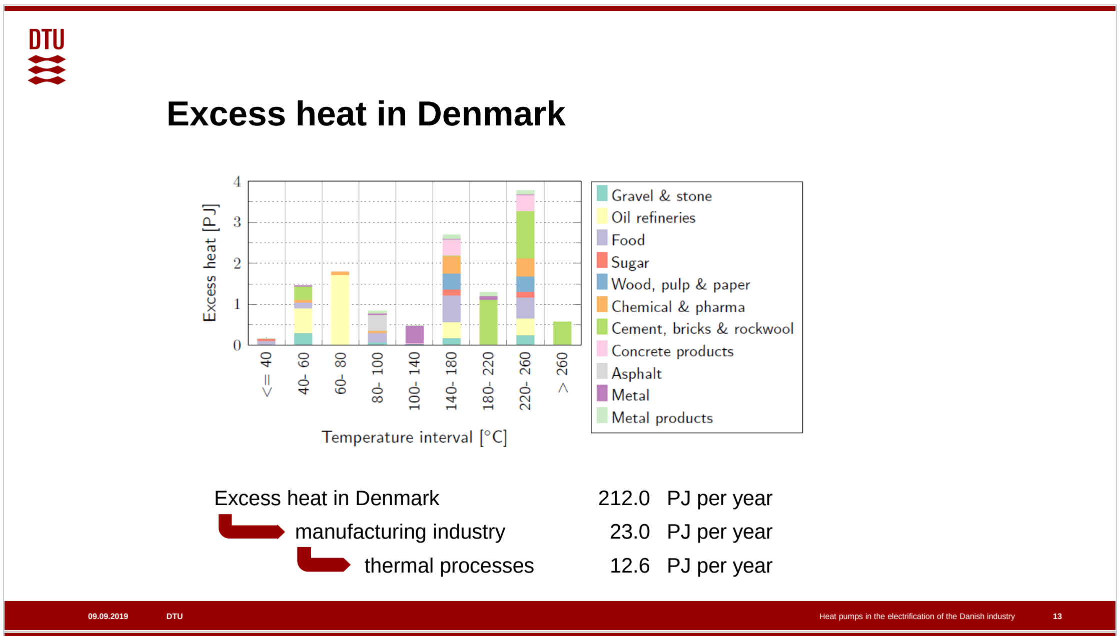
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Excess heat in Denmark
Excess heat [PJ]
0
1
2
3
4
<= 40
40- 60
60- 80
80- 100
100- 140
140- 180
180- 220
220- 260
> 260
Temperature interval [°C]
Gravel & stone
Oil refineries
Food
Sugar
Wood, pulp & paper
Chemical & pharma
Cement, bricks & rockwool
Concrete products
Asphalt
Metal
Metal products
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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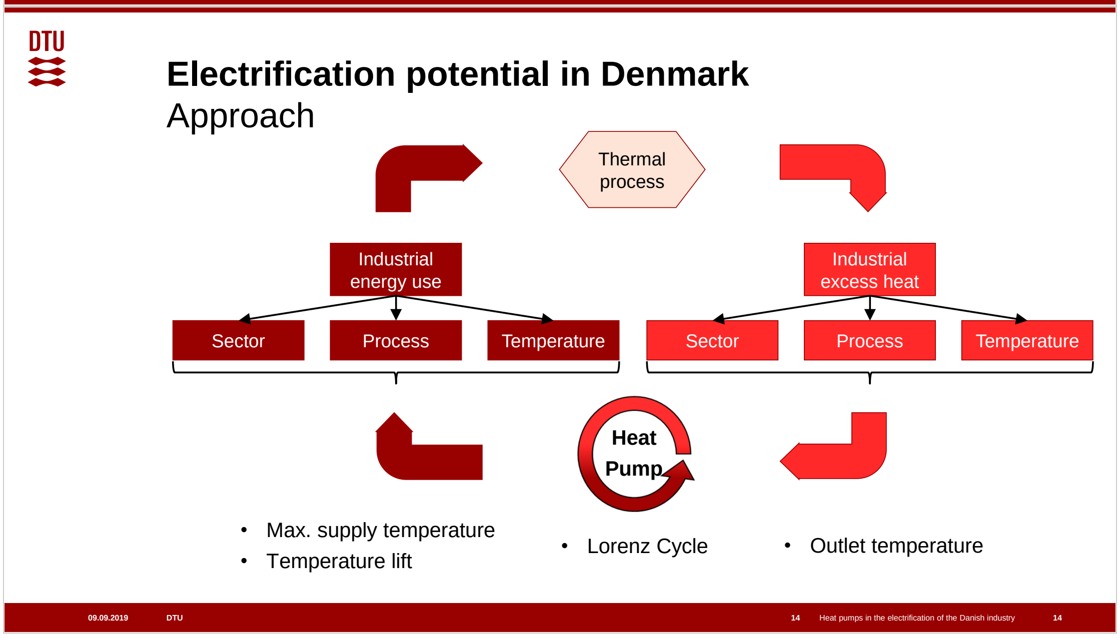
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Electrification potential in Denmark
Approach
Thermal process
Industrial energy use
Industrial excess heat
Sector
Process
Temperature
Sector
Process
Temperature
Heat Pump
• Max. supply temperature
• Temperature lift
• Lorenz Cycle
• Outlet temperature
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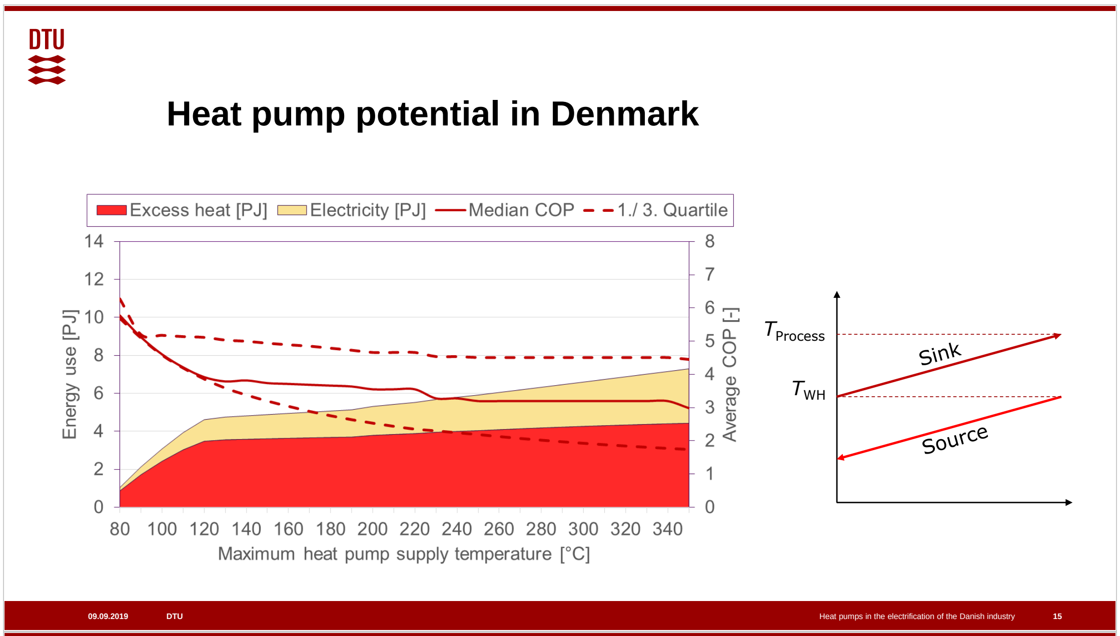
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Heat pump potential in Denmark
Excess heat [PJ]
Electricity [PJ]
Median COP
1./ 3. Quartile
Energy use [PJ]
Average COP [-]
Maximum heat pump supply temperature [°C]
$T_{Process}$
T_{WH}
Sink
Source
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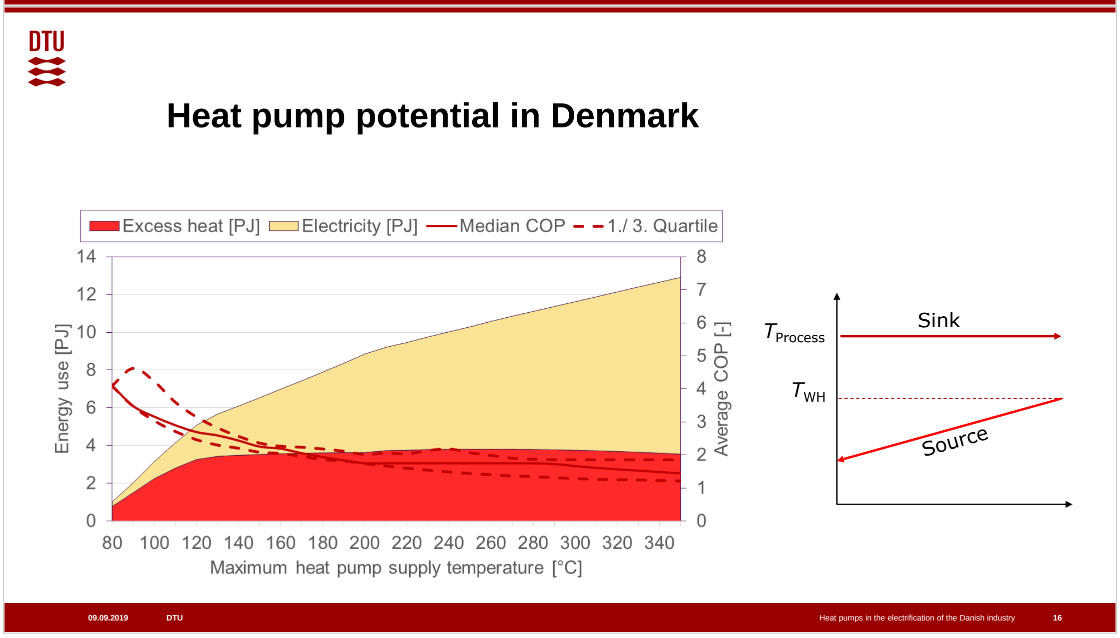
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Heat pump potential in Denmark
Excess heat [PJ]
Electricity [PJ]
Median COP
1./ 3. Quartile
Energy use [PJ]
Average COP [-]
Maximum heat pump supply temperature [°C]
$T_{Process}$
T_{WH}
Sink
Source
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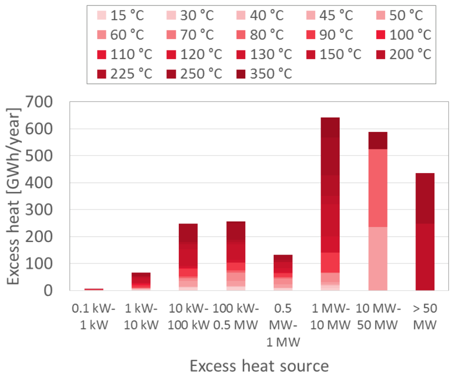
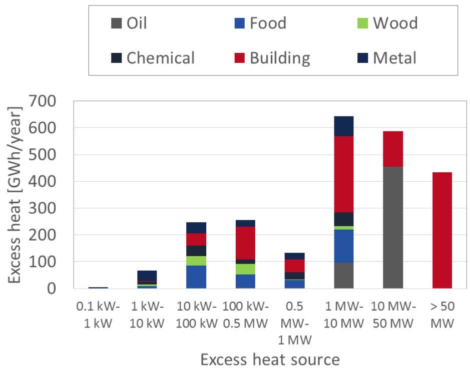
Excess heat sources in Denmark





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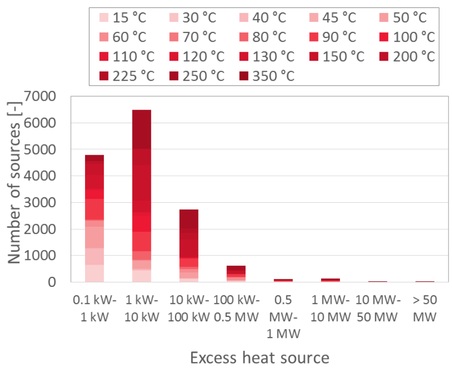
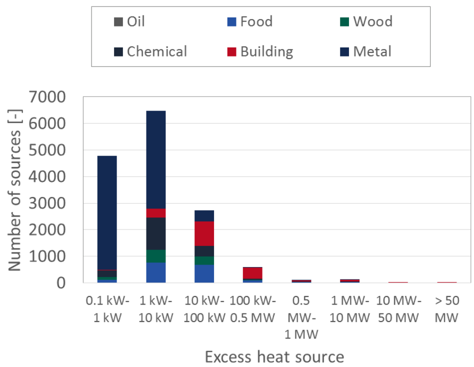
Excess heat sources in Denmark





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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!

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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.

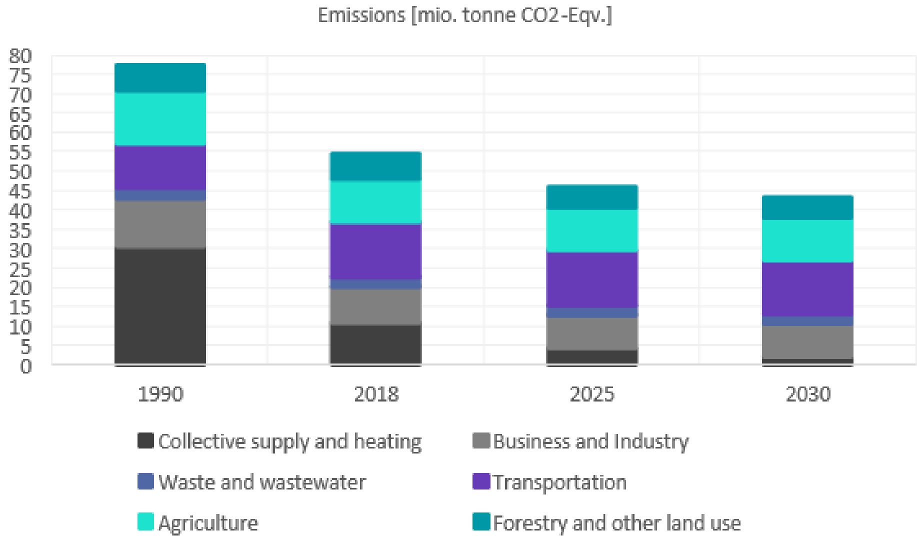

Figure 1 Development of the CO2 emissions from various Danish sectors. [5]

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.

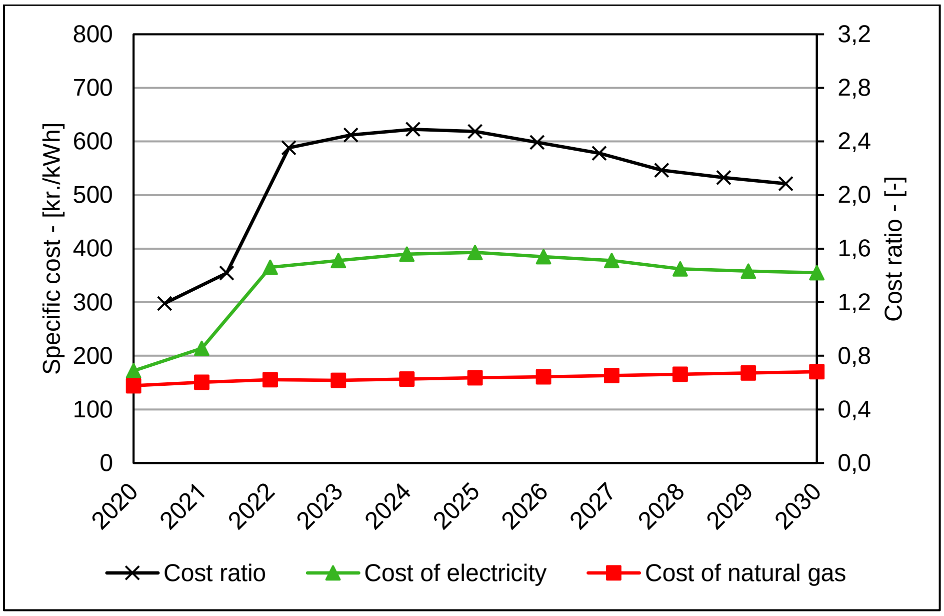

Figure 3 Expected development of cost of electricity and natural gas in Denmark. [9]

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 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.

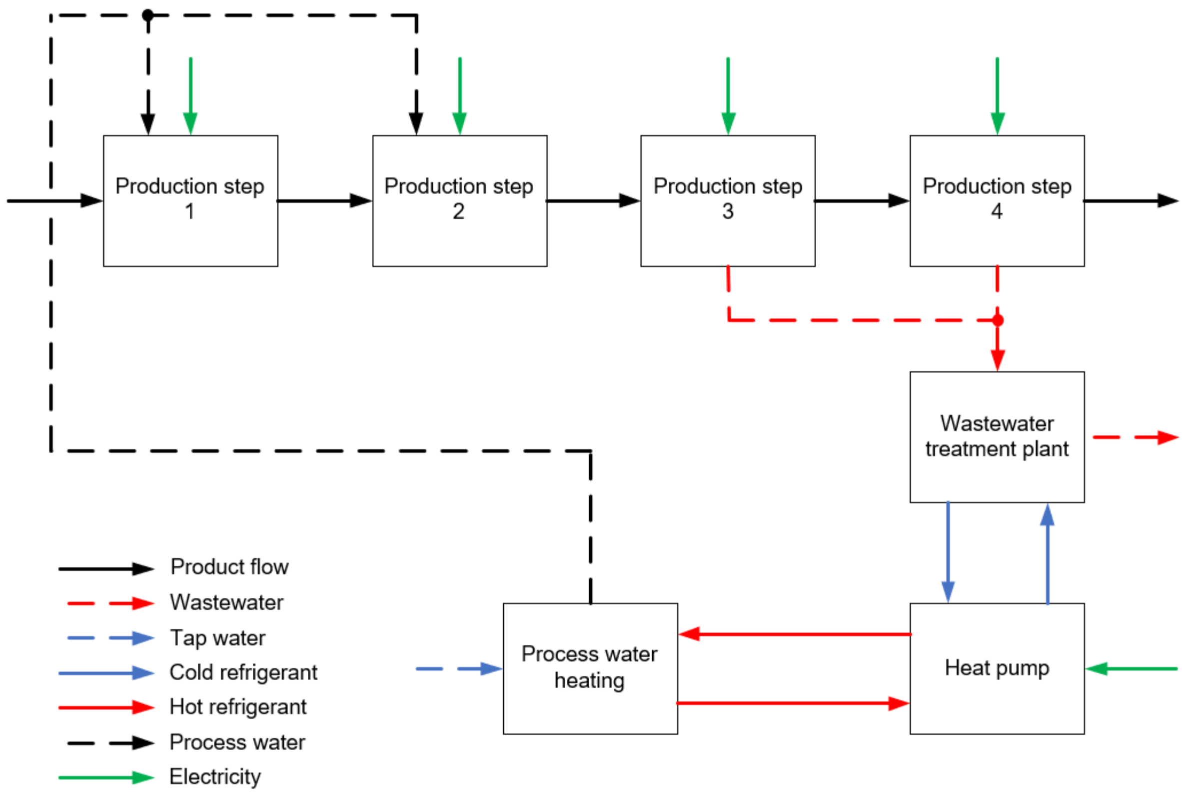

Figure 4 Example of an electrified process.

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.

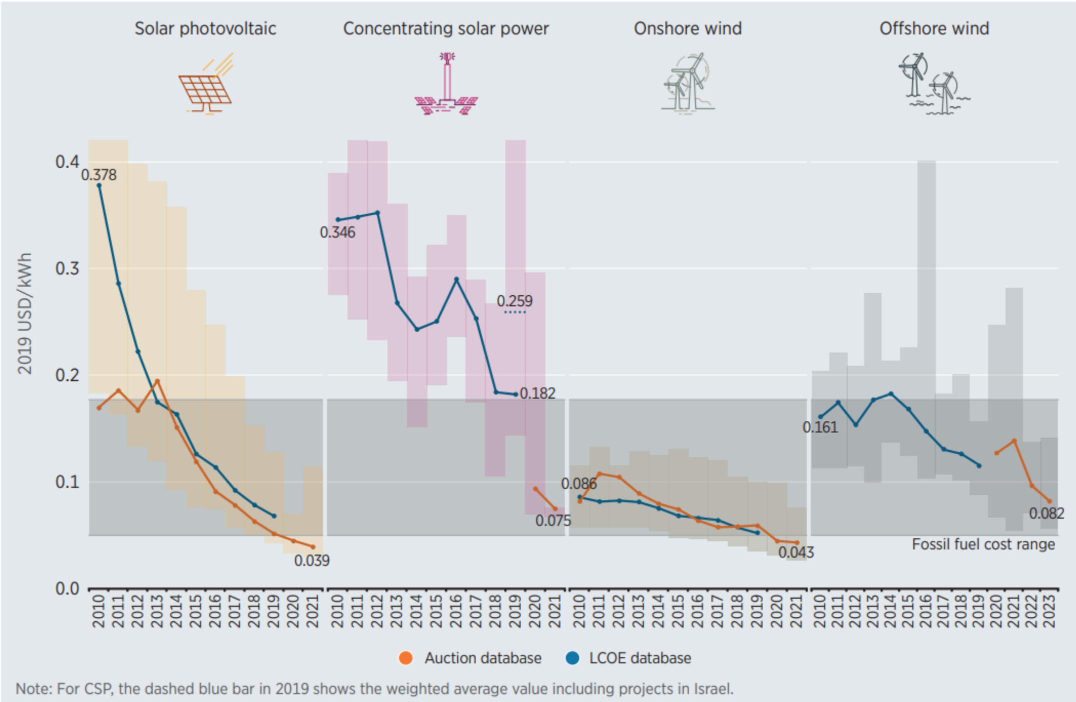

Figure 5 Global weighted average LCOE and Auction/PPA prices for CSP, onshore and offshore wind, and solar [25][1]

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 renew-able 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.

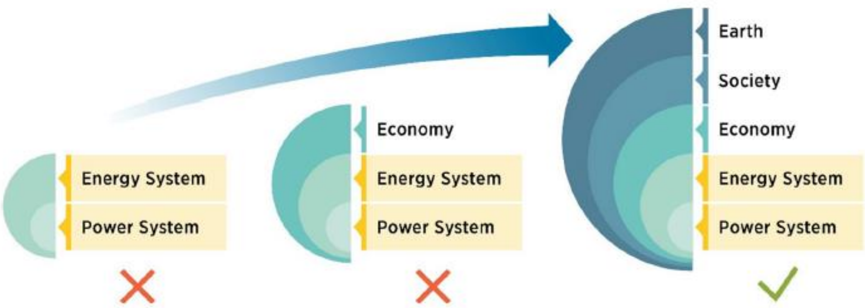

Figure 6 Power and energy systems as a part of a broader system. [25][2]

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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]

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.

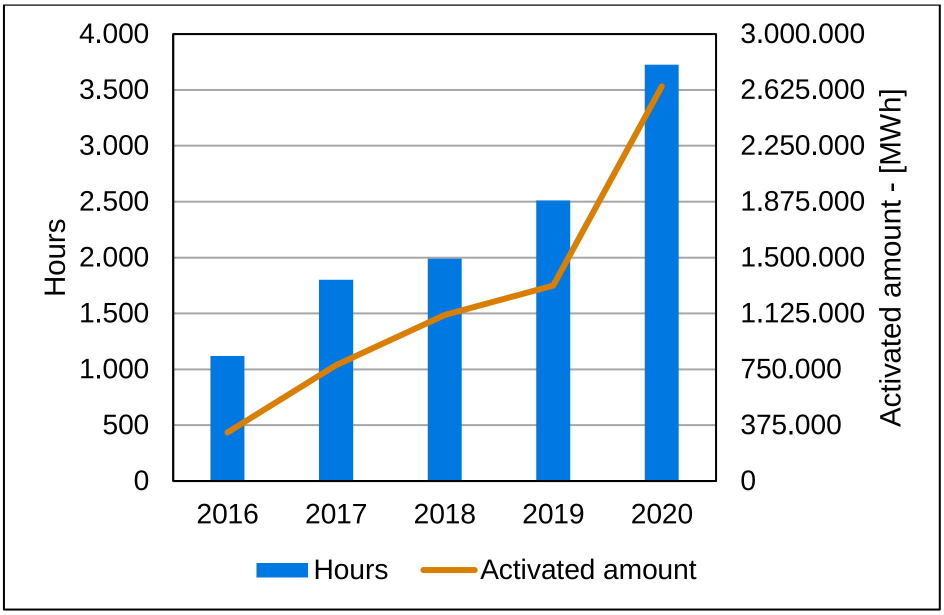

Figure 7 Development in special regulation of the Danish electricity grid.

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]

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Viegand Maagøe

Welcome

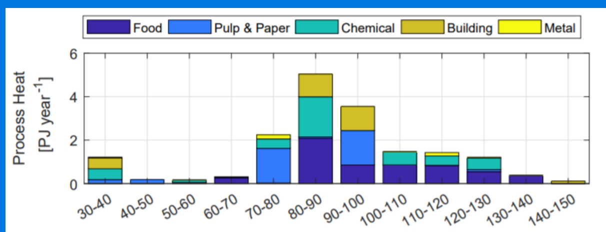
Bottlenecks for electrification

Viegand Maagøe

Background

Experience from the industry

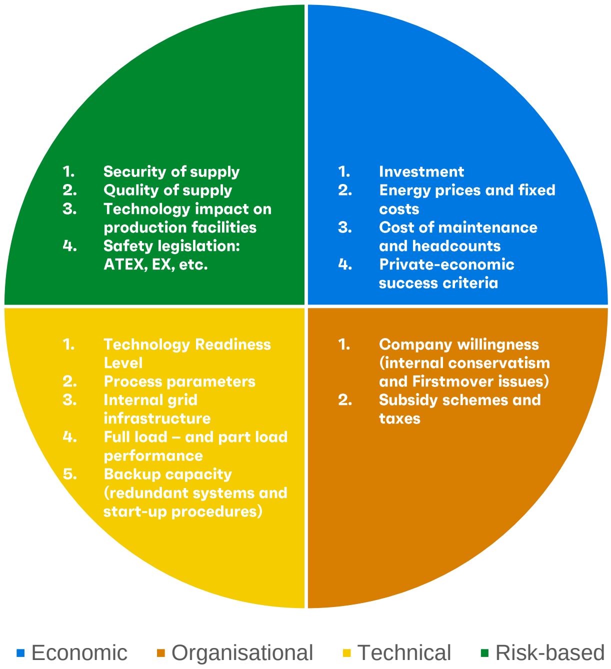
- Many processes below 100 °C can be electrified by heat pumps
- Most thermal processes are traditionally heated by various heat transfer fluids
- CO_2 emission from the Danish industry is not expected to decrease much towards 2030
- Electrification can act as a tool to decrease emissions while securing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



Bottlenecks for companies

Experience from the industry

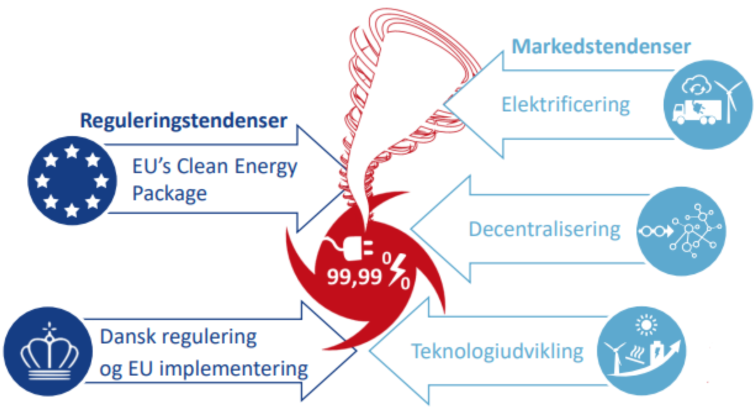
- Security of supply and – quality
- Some processes are easier to electrify than others
- Energy prices and investments are problematic to successful electrification
- "Technology Readiness Level"
- Conservatism and success criteria
- Subsidy schemes, taxes, and fees



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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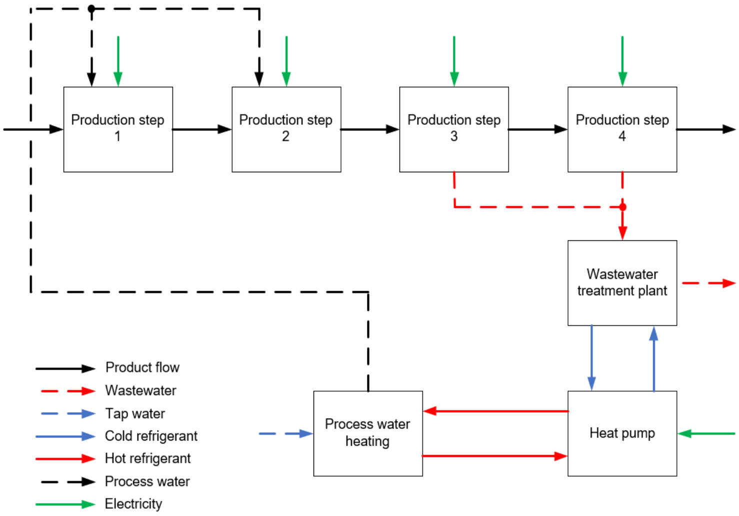
Processes and integration

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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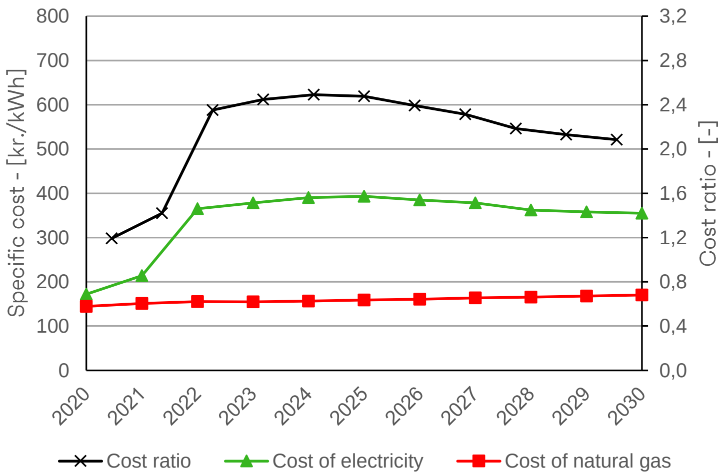
Energy prices

Experience from the industry

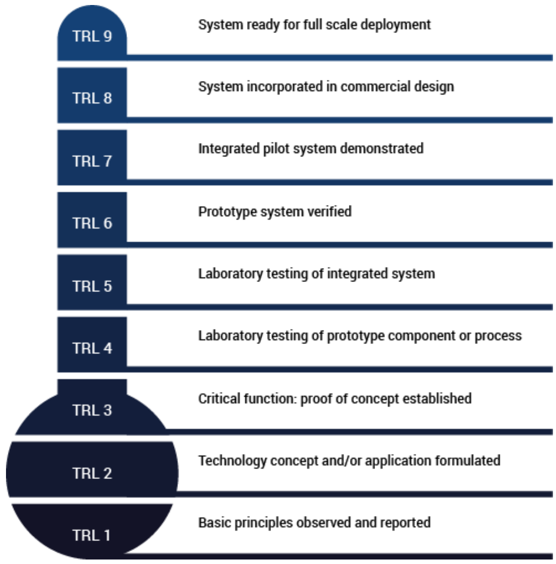
- Overriding barrier is the economy
- Spot prices from "Basisfremskrivningen"
- Including taxes, fees etc. the price ratio only decreases by approx. 5 % - (average Danish manufacturing company)
- For companies in EU ETS, cost of natural gas only increase by approx. 9 %
- In 2030, an electrified technology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



"Technology Readiness Level" - TRL

Experience from the industry

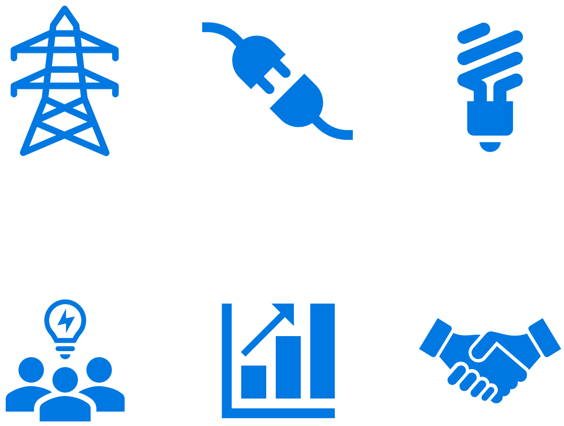
- Several processes have "plug-and-play" electrified solutions, i.e., evaporation, baking, drying etc.
- A large part of thermal processes are heated by central utility systems which can be electrified
- Electric boilers can be integrated as central utility systems → Not a feasible solution
- Technologies 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?



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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

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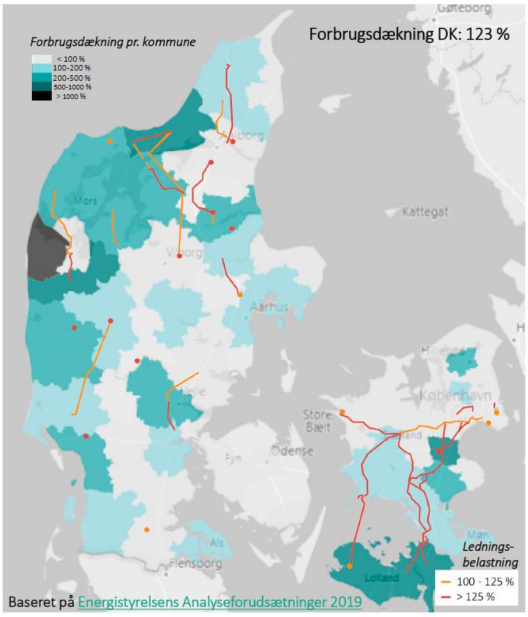
RES characteristics and security of supply

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.

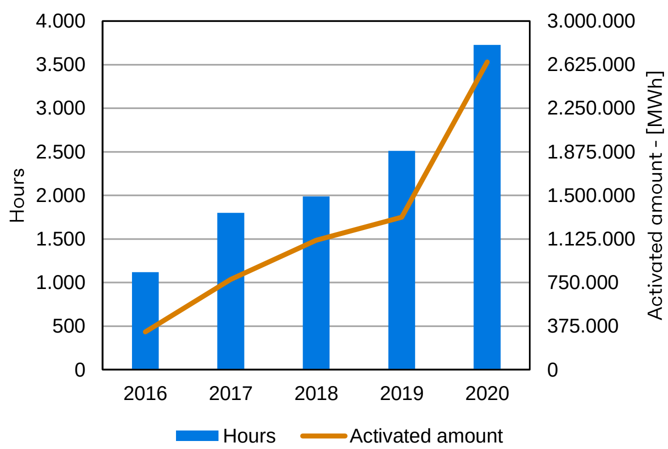
Thomas Egebo

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



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Thanks

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