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

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

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

2. Electrification in the industry

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

2.1. Industrial electrification options

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

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

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

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

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

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

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

2.2. Electrification potential

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

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

3. Material and methods

3.1. Energy use in the Danish Industry

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

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

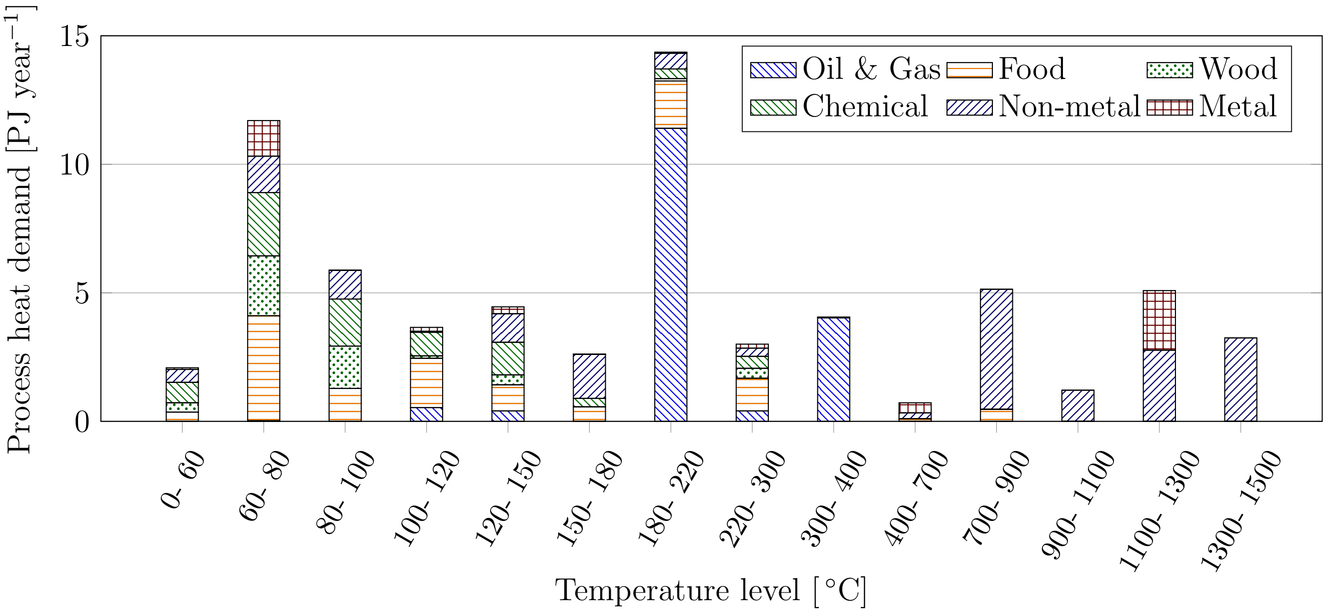


Figure 1: Industrial process heat demand by temperature level and sector in 2012. Based on data from [20, 21]

3.2. Determination of electrification potential

The electrification potential for the Danish manufacturing industry was established following the overall approach by Gruber et al. [13]. Based on the distribution of the heat demand amongst industries, processes and temperature levels, the electrification potential was established using suitable technologies established in Section 4.1. and cases from the literature. For the electrification of a given process different alternatives can be available as described in Section 2.1., depending on the situation at the production site. Additionally, some technologies may not be fully commercial yet or are based on a modification of the core process. Two scenarios were therefore investigated to account for these variations. A first scenario (Lo) considers established technologies and a low willingness to change the core processes. The second scenario (Hi) considers a high degree of technology availability and adoption. Both scenarios were compared to a business as usual (BAU) scenario.
As a large share of the process heat demand in Denmark is at low temperatures, heat pumps are expected to play an important role in the electrification. The COP of the heat pump is determined by the source temperature and type, which varies between industries and sites. It was assumed that heating demands up to 80 °C can be covered by ambient sources at 10 °C. Heat demands above were assumed to have a heat source with a gradual temperature increase up to 80 °C. Previous studies [22, 23] have shown that the majority of excess heat in the industry is available at temperatures below 100 °C. In the absence of sufficient excess heat, other heat sources (e.g. solar or district heating) could be utilised. The COP of the heat pump was

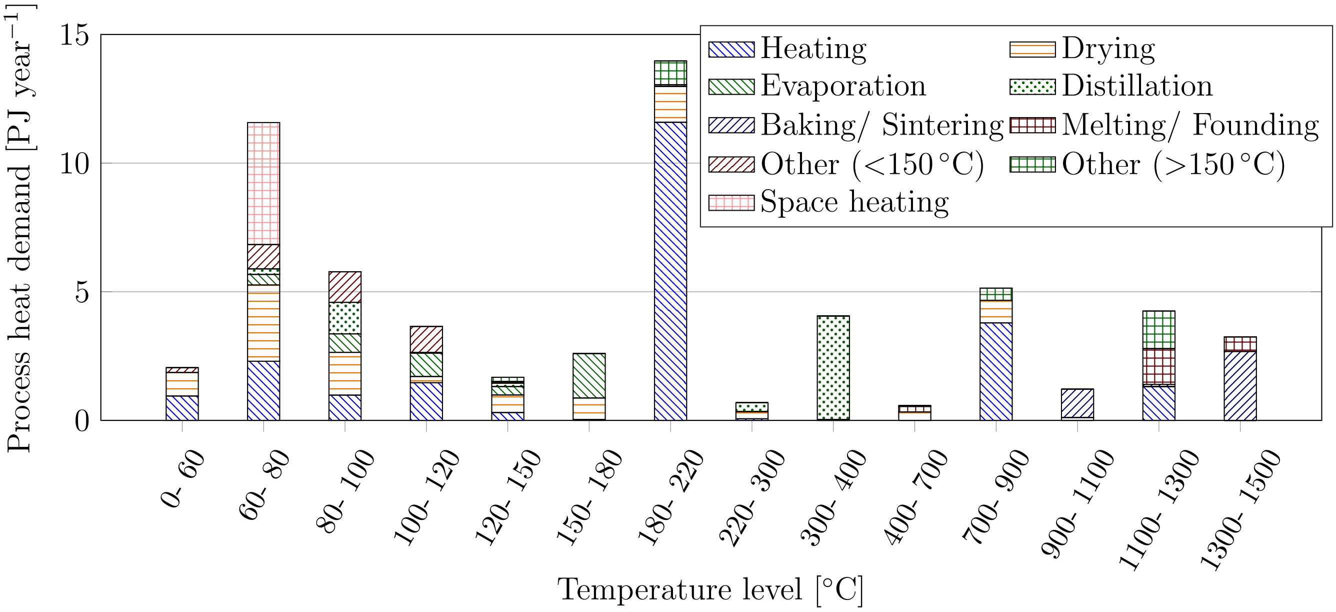


Figure 2: Industrial process heat demand by temperature level and process in 2012. Based on data from [20, 21]

found using the Lorenz efficiency, with an efficiency of 45 %. The required temperature lift was always from the lower to the higher temperature of the temperature band shown in Figure 1 and 2.

The CO_2-emissions of the industry were found using the emissions factors of the fuels [24] used in the industry sector. For electricity the current emission factor in Denmark and the one expected for 2025 were used [25].

3.2.1. Low technological development scenario (Lo)

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

3.2.2. High technological development scenario (Hi)

This scenario assumes that process alternatives can be developed for all processes which require thermal energy. In addition to the previous scenario it was assumed that HTHP can supply process heat up to 400 °C, in the form of steam, air and thermal oil. Using the MVR for evaporation and heat pump distillation was a possibility in all cases.

Based on literature case studies [10] electric-options for other process heating demands were used. This included for example microwave technology to substitute 50 % of energy use in kilns and furnaces. IR drying of materials, reducing energy use by 45 %. Also in the cement production electric heating was possible for parts of the production and increased efficiency by 12 % [26].

4. Results

4.1. Electrification technologies

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

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	+

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

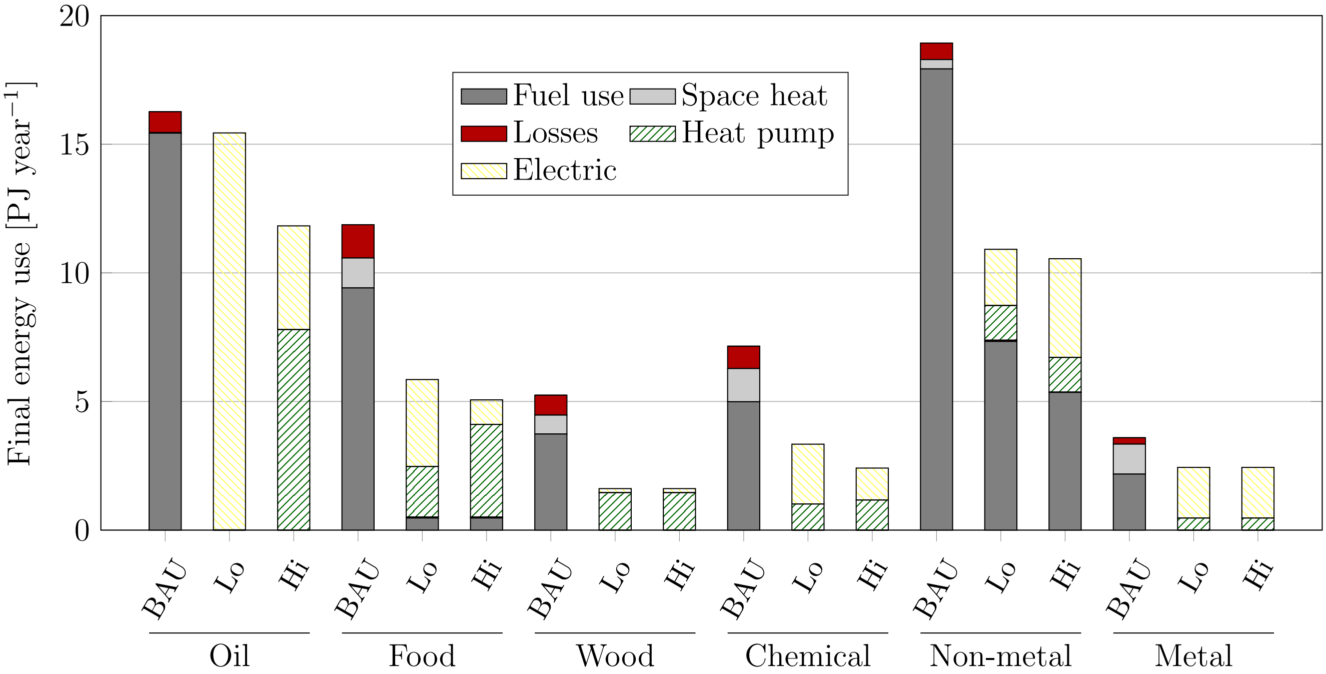
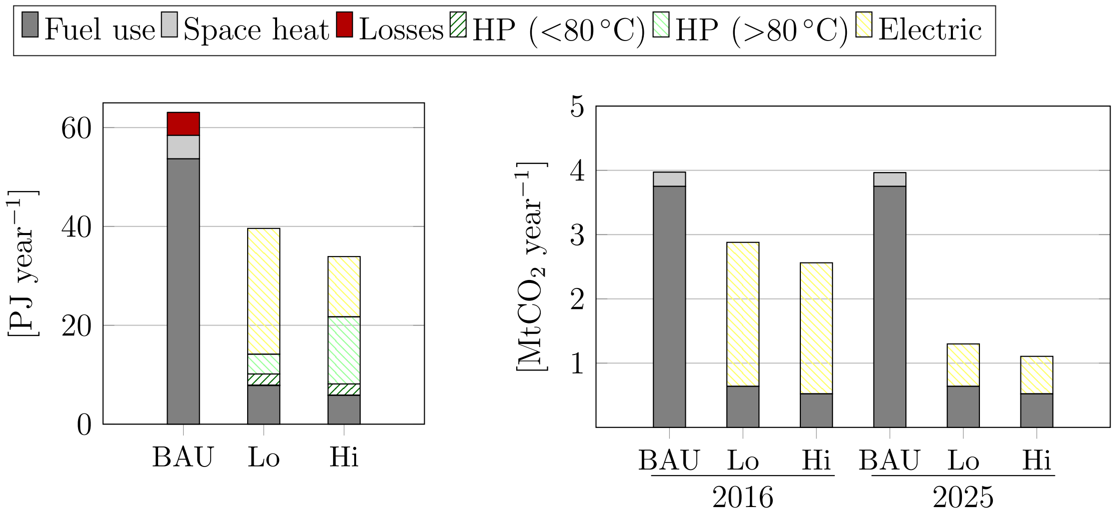


Figure 3: Final energy use for heating in the main industry sectors in Denmark for different scenarios. "BAU" desribes the current system, "Lo" and "Hi" the electrified systems.

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

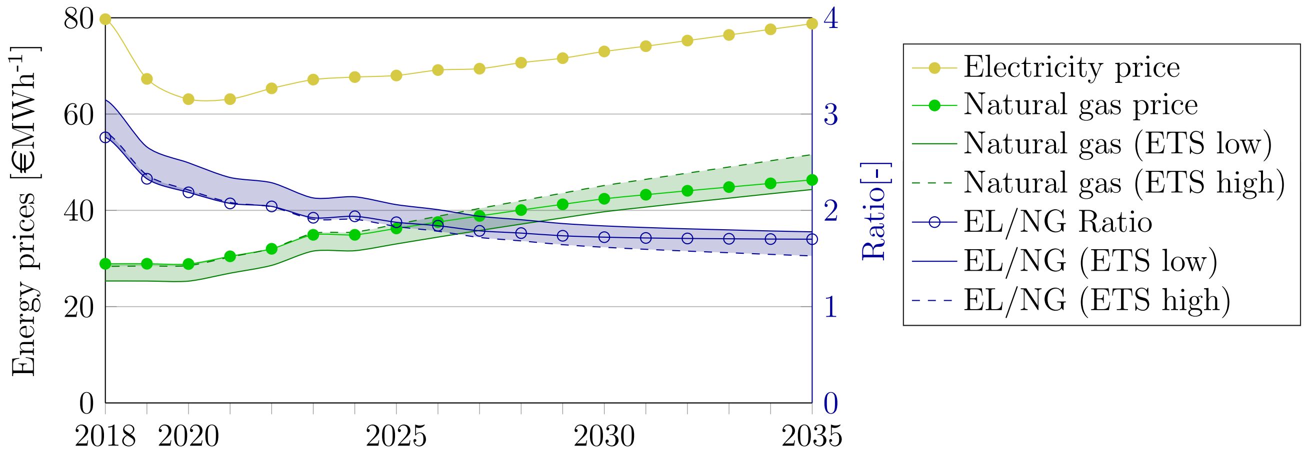
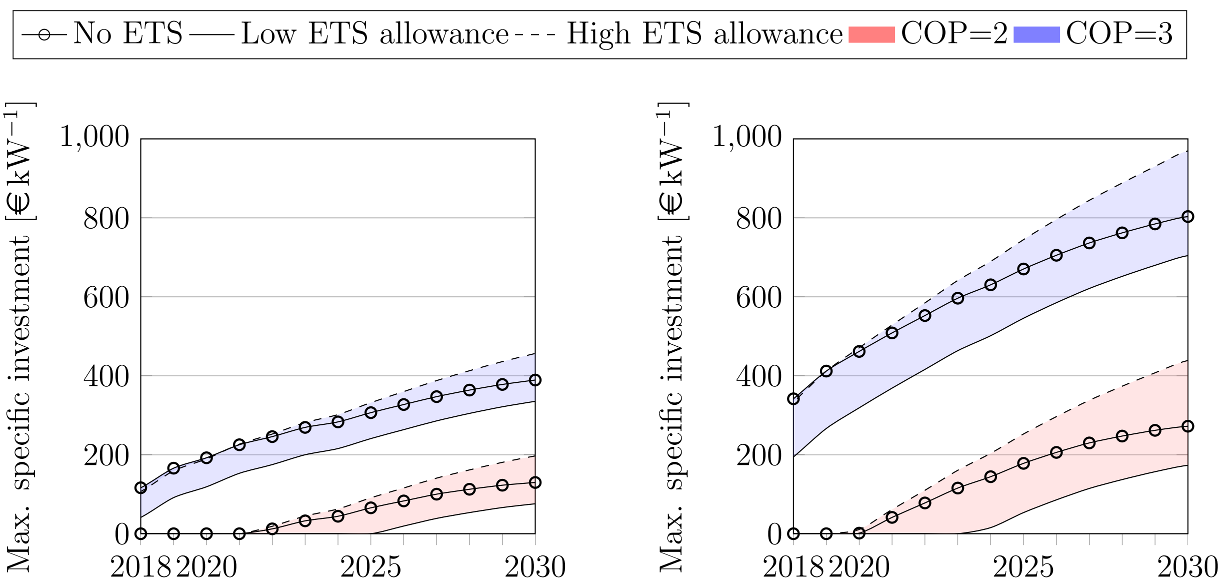


Figure 5: Development of energy prices for industrial process heat in Denmark until 2035 and the ratio between Electricity and natural gas. The addition of (ETS) indicates the inclusion of low and high costs for CO_2 allowances.



(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.

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Nomenclature

BAU Business as usual

COP Coefficient of performance

Hi High technology scenario

HP Heat pump

HTHP High temperature heat pump

IR Infrared

Lo Low technology scenario

MVR Mechanical vapour recompression

RF Radio frequency

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