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Electrification of industrial processes with low-to-medium temperature heat demand: Case study of pectin production

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Abstract:

The article presents an approach for complete electrification of processes in the low-to-medium temperature manufacturing industry, for which the Danish pectin production factory CP Kelco was used as a case study.

The electrification analysis of CP Kelco was carried out by first proposing eight varieties of complete electrification strategies to undergo a screening process. Among the strategies, 3 performed better and were selected for detailed analysis in terms of final energy use and economical and environmental indicators. Compared to Business as Usual (BAU), two cases with - and without Mechanical Vapour Re-compression (MVR), reduced the yearly final energy use by 50 % and 33 % with a simple payback time of 6.2 years and 7.3 years respectively. The third case, concerning grassroot implementation of MVR for evaporation and distillation, and local, off-the-shelf heat pump systems, reduced the yearly final energy use by 69 %. The implementation of the technologies in the third case was gradual implemented through 25 years with a maximum payback time on sub-investments of 3.9 years.

Finally, the article presents the main bottlenecks for electrification learned from the CP Kelco case. The main approach proposed in the general electrification strategy was: (i) replace inefficient technologies with alternative technologies for energy savings, (ii) identify utilisation of heat pumps, and (iii) identify alternative technologies for remaining central utility demands.

Keywords:

Energy efficiency, Decarbonisation, Electrification, process integration, Heat pump

1. Introduction

To reach the goal of a global European climate neutral society before 2050 as stated by the European Commission in [1] severe measures should be taken across all sectors towards strong and swift actions to reduce Greenhouse Gas Emissions (GHGE). The industrial sector, to a great extent, relies on the combustion of fossil fuels to supply e.g., process heat and space heating. It has been shown that in countries with a high share of sustainable energy in the electricity mix, GHGE reductions in the manufacturing industry could be carried out by means of electrification [2,3]. This could be achieved by the use of electric driven technologies, such as electric boilers, heat pumps, electric drives for turbo machines, MVR, resistance -, infrared -, and microwave heaters, etc. [4]. It is predicted by [2], that electrification will take over as the largest contributor to CO_2 emission reduction by 2030.

Utilising electricity for heating purposes in the industry can lead to great energy savings [5,6], as electric heating methods can target energy precisely where it is needed at almost any temperature, thus reducing heat losses significantly. However, even though electricity has many advantages and is very versatile, electrification of thermal processes in the Danish manufacturing industry faces both technological and economical challenges, which have shown to be interconnected. It is found that within food production and processing, around 1200 TJ of heat is yearly lost in terms of excess heat in the temperature interval of 80 °C – 100 °C [6]. The excess heat could be utilised in direct heat recovery by means of process integration with pinch analysis or by the implementation of heat pumps. The process heat demand for the food industry terminates at temperatures of around 240 °C and is particularly dominant within the temperatures of 80 °C - 120 °C [7].

This is commonly the heat demand of processes such as evaporation, separation, process water heating and drying. These temperatures could potentially be covered entirely or partly by the implementation of heat pumps, either implemented centrally for steam generation purposes as presented in [8] or locally for direct preheating or complete covering of process heat demand within the state-of-the-art condensation temperatures, which are most commonly below 100 °C [5]. The electrification of the manufacturing industry is an area which is not well studied and to which, a general methodology is yet to be formulated. Therefore, the results and experiences from an electrification analysis of CP Kelco could aid the foundation for a future general approach. The work is summery of a master project [9], which has been done at section of thermal energy, Department of Mechanical Engineering, Technical University of Denmark in 2020.

2. Method

2.1. Case study and process description

The following section presents general information on the CP Kelco factory, the world's largest pectin factory located in Denmark acting as a case study. An overview of the production flow is presented along with a brief description of the processes involved. The factory produces three different types of products, pectin, carrageenan, (P, C), and Locust Bean Gum, (LBG). The first two products are each divided into two types: (LM, HM), and (C2, C3) respectively. The final products are used in food products as an agent or a stabiliser. The total production of P, C, and LBG products is about 4.025, 706 and 2.000 tonne/year respectively. The factory operates almost non-stop throughout the year on various production lines. In addition, it operates its own CHP plant, which has a final energy use of 378 GWh equivalent of natural gas annually to generate electricity and supply 7 bar(g) steam for the processes. The steam is used in steam condensers and direct steam injection. The factory also delivers heat to a nearby district heating network. The delivered heat is excess heat from on-site alcohol distillation columns explained below. The factory production system consists of four main processes, namely extraction, evaporation, precipitation/separation, and drying sections and three service processes, namely distillation, space heating, and CIP (Cleaning in Place). The production steps and utilities are already interlinked in several ways of internal heat recovery and district heating production. Therefore, alterations in utility or production technologies could have both negative and positive effects on other interconnections further downstream. The overall product flow and the main utilities for the processes are presented in Fig. 1 and briefly outlined in the following.

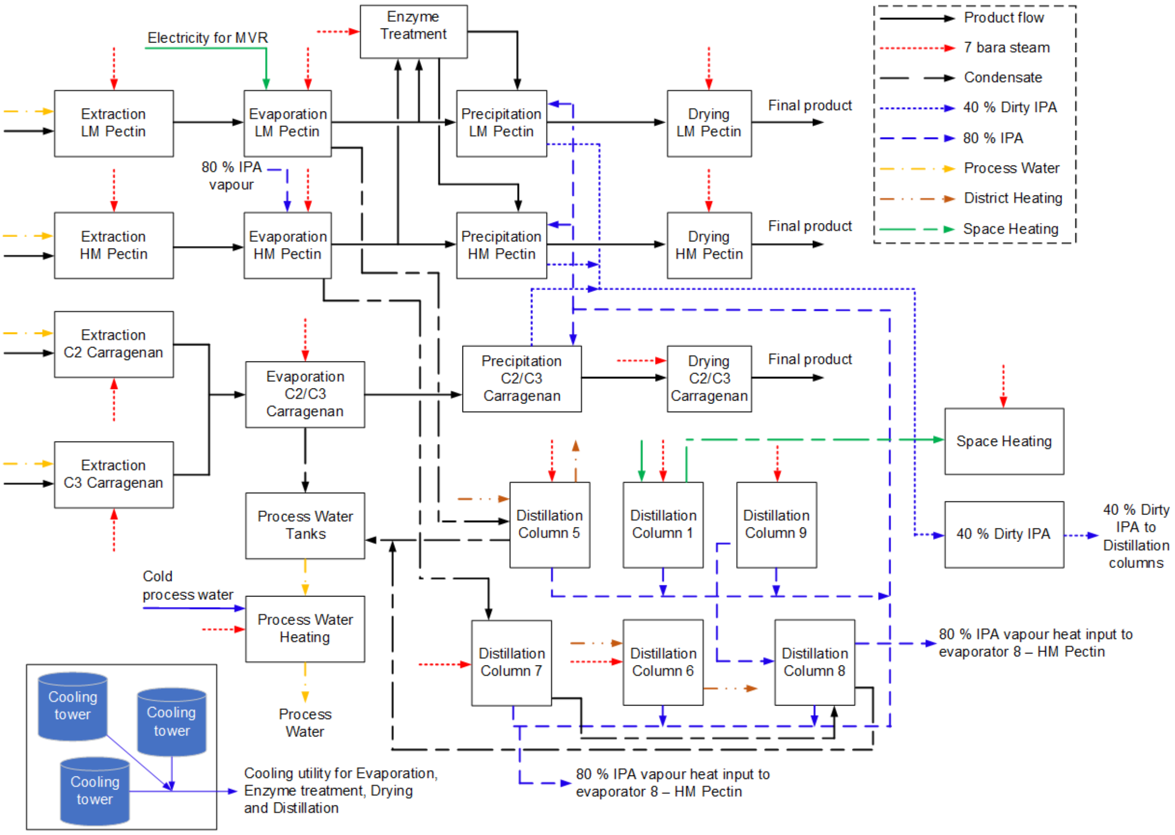


Fig. 1 Product flow and utility chart for processes at CP Kelco without Locust Bean Gum production.

In the extraction section, pectin is extracted from citrus peels and carrageenan from seaweed. After the extraction, the remaining product streams called “thin juice” are concentrated in evaporation sections, where water is evaporated to obtain a more concentrated product stream, referred to a” thick juice”. The concentrated streams then undergo precipitation where alcohol is added. The factory has five evaporators of different kind, one MVR and four TVR’s. The evaporated water from LM - and HM pectin evaporation is condensed by internal heat recovery and cooling towers, whereafter the condensate is led to distillation column 5 and 7 respectively.

In distillation column 5 the condensate is heated by condensing 80% alcohol vapour and afterwards led to process water heating by steam, to act as process water for the production. The water/alcohol mixture has a concentration of around 40 % alcohol by weight and is sent to the distillation columns to increase the concentration to reach 80 % from the precipitation section, the product streams are dried to the final product. At the factory, some of the condensation of alcohol is done by heat exchanging with other processes as e.g., process water, space heating and as heat source in heat pumps for district heating production. The total energy demand for space heating is 18.6 GWh per year, of which 3.9 GWh is covered by cooling of the distillation process and the remaining is covered by steam condensers.

2.2 Energy analysis and Electrification Strategies

The entire study is based on a thoroughly performed energy mapping of CP Kelco, consisting of mass flow rates (tonne/year), heat rates (kWh/year) and temperatures throughout the processes. All mathematical models of processes used in the energy analysis are fundamentally based on mass conservation and the 1st law of thermodynamic for an open system and steady state conditions and solved numerically.

In the next step, the material streams involved in the energy mapping are analysed in terms of pinch analysis, to clarify the question of whether the heat integration from pinch analysis a natural and beneficial starting point for successful electrification. The traditional method by Linnhoff [10,11] and the SSP (Specific Savings Potential) method from [12] are used for the pinch analysis. The pinch analysis and the SSP method led to a reduced Heat Exchanger Network, (HEN), which is not included in the present article. After the pinch analysis, several options for full electrification of CP Kelco are screened with regards to electricity consumption and system complexity. The electrification screening consists of cases with various technologies, with - or without heat recovery. Then, a detailed energy analysis of the selected cases was performed, e.g., by modelling technologies to achieve more realistic and thorough results. Finally, the cases chosen for further analysis were evaluated in terms of economy - and environmental indicators.

The proposed electrification cases are presented in Table 1. The technologies, which have been considered for the electrification technologies are: Central steam generation with heat pumps and cooling demand to both production - and service processes; Local heat pumps for covering the heating and cooling demand below 85 °C at the respective processes.; MVR in evaporation and distillation processes for reduction of steam use; Central and local electric boilers for steam generation. In one of the cases, the district heating agreement is no longer in effect and all excess heat from the processes is utilised as heat source for local heat pumps along with ambient heat.

Table 1 Technology overview for the eight cases involved in screening analysis.

Cases	1A	1B	1C	1D	2A	2B	2C	2D
Local HP	X	X	X	X	X	X	X	X
Central steam generation HP	X	X			X			
Heat integration from pinch		X		X				
Electric boiler			X	X				X
MVR evaporation					X	X	X	X
MVR distillation retrofit							X	
MVR distillation new								X
District Heating production	X	X	X	X	X	X	X	

Case 2D assumed the factory to leave the district heating agreement, when possible, and the electrification strategy was split into 4 steps, starting from year 2020 to 2045 with a time domain of every 10 year. The cases chosen for further analysis are presented in Fig. 2 below.

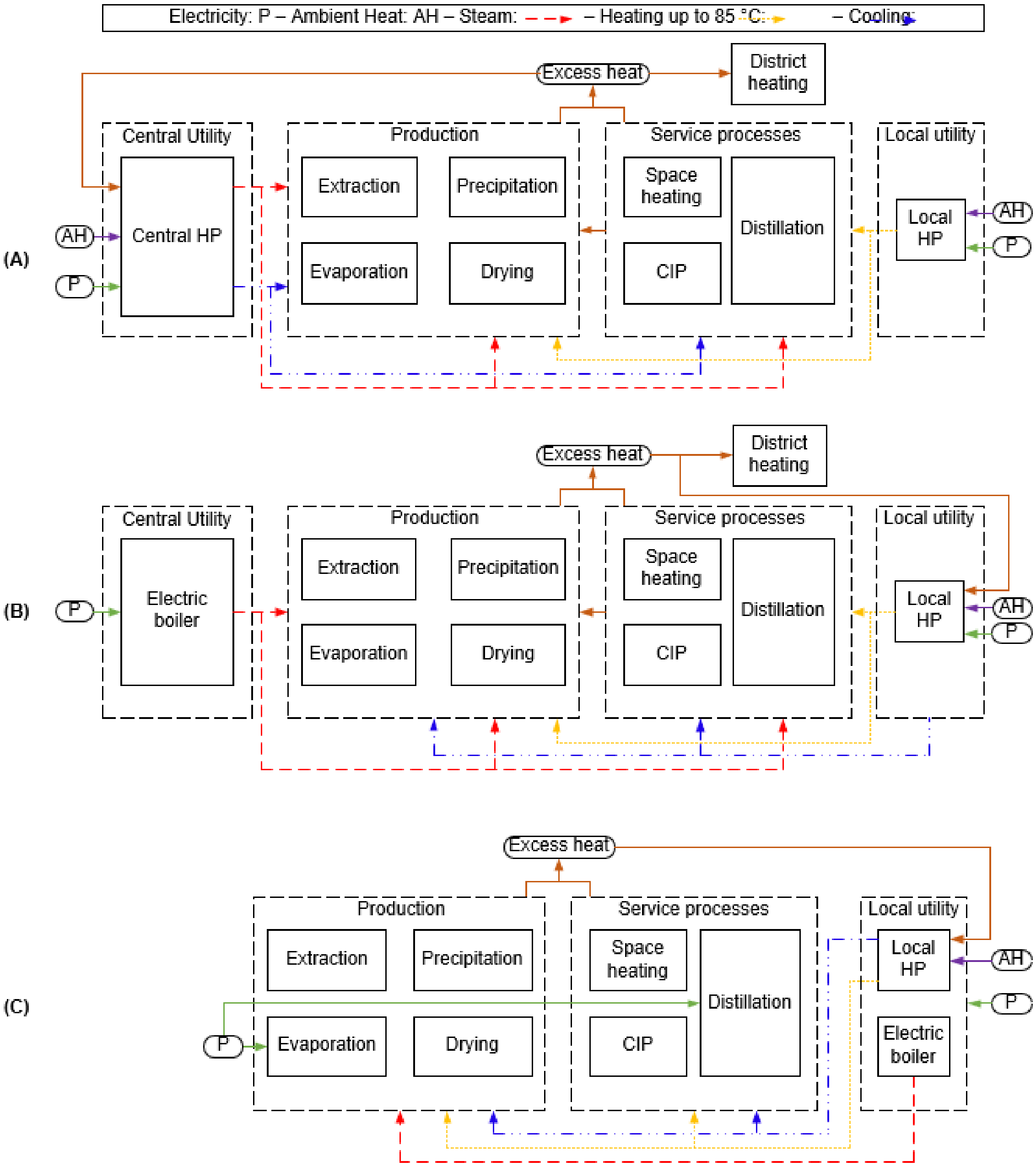


Fig. 2 Electrification cases of CP Kelco: (a) Case 1A, (b) Case 1C, (c), Case 2D.

2.3 System modelling and assumptions

The following assumptions are taken to model the system and evaluate the electrification cases. Ambient air with yearly average temperature of 6 °C [13] was considered as a heat source in all the mathematical models. In the screening process, the heating demand for process water and district heating was fitted theoretically to the cooling demand for optimum heat recovery. Furthermore, heat and pressure losses were neglected in all the calculations. However, in detailed analysis, the existing heat exchange connections were preserved unless the process technology was replaced by new or retrofitted. The cooling demand was covered by cooling loops with different temperature levels, which were considered as a heat source for the central HP or local HP's. The heat exchanging between the cooling loops, cooling utility consumers and HP's were assumed to have a minimum temperature difference of 5 K and 7.5 K based on recommendations by [14]. In addition, in the detailed analysis, the heat losses related to 1 bar(g) steam pipes were also taken into consideration.

The heat demand under Business as usual (BAU) shows that the evaporation and distillation technologies have a final energy use of 75 % of the total natural gas use and 75 % of the steam produced at the local CHP plant at CP Kelco respectively. Furthermore, the total cooling demand is roughly half the heat consumption in which the distillation and evaporation sections account for 95 % of the cooling demand.

The models of technologies built for evaluating of the electrification cases are briefly explained in the following. Detailed information of the models can be found in [9]. Apart from heat pump models, all the models of technologies built in the screening phase are also used in (detailed) analysis. The isentropic efficiency (η_{is}) and the power consumption of the compressors (P) in this work are defined as presented in Eq. (1) and (2) respectively. The compressors are assumed to operate with an isentropic efficiency of 75 %, while the gear and the motors are assumed to have an efficiency of 95 %. These assumptions are used in all the models such as MVR evaporator, MVR distillation column retrofit, and central system generation and local heat pumps. Where h is specific enthalpy and the subscript (in) and (out) denotes conditions at compressor inlet and outlet respectively.

$$\eta_{is} = {(h_{out,is} - h_{in})}/{(h_{out} - h_{in})} \quad and \quad P = {\dot{m}(h_{out} - h_{in})}/{\eta_{gear}.\eta_{motor}} \qquad (1) \text{ and } (2)$$

Electric boilers: Electric boilers are assumed to have 100 % energy efficiency.

MVR Evaporators: The MVR evaporator, a falling film evaporator, is modelled as a single effect MVR with operating pressure of 0.319 bar(a). The amount of water evaporated is determined by a thin to thick juice ratio. In addition, the heat and pressure losses are neglected in the MVR model. The pressure after the vapour compressor is assumed to be 5 K above evaporation temperature. In addition, the falling film heat transfer area is calculated with Eq. (2), where $\dot{Q}$ is the energy needed for evaporation which can be supplied from the latent heat of condensation from the re-compressed vapour. In addition, the heat transfer coefficient U, and the temperature difference ΔT for calculating the logarithmic mean temperature difference ΔT_{LM} are equal to 2200 W/m^{2}K and 5 K, selected based on recommendations by [14].

$$\dot{Q} = U.A.\Delta T_{LM} \qquad (3)$$

MVR distillation columns – retrofit and grass root: A retrofit design of distillation column 5 is proposed to supply the same amount of energy to the district heating while reducing the steam consumption in the distillation process. This is obtained by compressing 80 % IPA vapour, from the top of the distillation column, and utilising the condensation energy in a reboiler, a pressure corresponding to a condensation temperature of 120 °C. This design leaves the distillation process in need of steam, which will be provided from the central utility system.

In the grass root deseing like the retrofit one, 80 % IPA is lead from the top of the distillation column and through compressors and into the re-boiler, however no additional energy is required, and the primary steam is only used during the start-up phase.

Heat pumps: In the screening approach, the estimation of power consumption for the heat pumps is based on Eq. (3), where $\dot{Q}_{sink}$ is the heat consumption of the sink and COP is the coefficient of performance. The COP is estimated based on the Lorenz COP [15], assuming Lorenz efficiency of 0.5 as it is stated in Eq. 4. However, in the detailed analysis of selected cases, a detailed HP models are applied, as explained below.

$$P_{compressor} = {\dot{Q}_{sink}}/{COP} \quad and \quad COP = \eta_{Lorenz}.COP_{Lorenz} \qquad (4) \text{ and } (5)$$

Heat pump steam generation system:

The central heat pump based steam generation system, supplying both 1 bar(g) and 6 bar(g) steam to the production processes, was modelled, and consisted of bottom heat pump cycles, a central evaporator and a steam compression unit on top, based on a system presented in [16]. The bottom cycles utilised different heat sources and supplied heat to the evaporator at 90 °C. The central evaporator is operated at sub-atmospheric pressure corresponding to 0.6 bar(a), and the steam is then compressed in multi stages compressors with a maximum pressure ratio of 3.5 [17,18].

The bottom heat pumps are divided into different temperature levels and types, according to the temperatures needed for cooling utility in the processes. For source outlet temperatures ≥ 20 °C a single stage heat pump is used, with R600a as working media. For larger temperature lifts with ambient as heat source a cascade coupled heat pump is chosen, with the working media for bottom and top cycles being R290/R600a respectively [19].

Local Heat pumps:

Local heat pumps are assumed to cover heating demands, where the target temperature is below 90 °C. As for the case of the central steam generation HP, the local heat pumps are modelled identically to the cascade bottom heat pumps with ambient as heat source. Otherwise, local heat pumps are modelled as regular bottom heat pumps and supplies heating as regular HP’s with ambient air as heat source, to add energy to the loop and consequently maintain energy balance between energy obtained by local HP’s and energy added by the cooling consumers.

2.4 Economic and Environmental analysis

To perform an economic evaluation of the chosen cases for the specific electrification analysis, it is necessary to estimate the TCI (Total Capital Investment). The chosen method for estimating the investment cost is by determining the bare module cost found in literature [20,21]. The standard purchased equipment costs C_P^0 were found with the module constants parameters k and size parameter x, presented in Eq. (5), using the bare module cost correlations found in literature and corrected according to several factors to obtain the TCI. The corresponding k values and assumptions and correction factors can be found in [8].

$$C_P^0 = 10^{k_1 + k_2 . \log(x) + K_3 . (\log(x))^2} \tag{5}$$

The operation and maintenance cost (OM), was assumed to be 1.7 MDKK/year for the boilers and turbine, estimated in collaboration with CP Kelco personnel. The OM for HP ’s was based on actual values for the HP connected to the District Heating (DH) network, which correspond to approximately 0.2 MDDK/MW/year.

CP Kelco is a part of the EU CO2 quota system [22], which yields that CP Kelco need a specific amount of CO2 quota corresponding to the emitted CO2. They receive free quotas and buys the remaining according to their emission. The CO2 quota price is interpolated between 2020-2030 and linearly extrapolated between 2030-2039, according to European Commission [23], the price will be around 40 €/ton in 2030. From 2020-2030 the electricity price is corrected from [24] to taxes and fees specific for CP Kelco. In the same manner, the natural gas price was found from [25] and corrected. Both electricity and gas prices were linearly extrapolated from 2030-2039. The inflation rate was also included from [24] and linearly extrapolated from 2030-2039. Finally, the profitability of the project was evaluated based on two performance indicators, Payback Time (PBT) and Net Present Value (NPV). The equations for estimation of PBT and NPV value can be found in [15]. In the present study, the discount rate of to 8.0 % [26] and the lifetime of to 20 years was assumed for all the projects. It is expected that the cash flow starts in year 1 of the investment. Also in year 1, an energy saving subsidy of 0.25 DKK/kWh is added to the cash flow, which is available for some Danish companies [27]. All economic analyses have 2020 as starting year.

The environmental analysis was based solely upon reduction in CO_2 emission. The CO_2 emission of natural gas was assumed constant to a value of 205 g/kWh [28]. The CO_2 emission of electricity vary a great deal based on the energy conversion process. In this work the EU reference scenario 2016 [29] was used as forecast for CO_2 emission of electricity. The analysis includes emissions for Denmark and EU-28 in the period 2020-2039.

3. Results

3.1 Energy mapping and pinch analysis

The energy mapping of the production processes showed that the highest temperature demand is 120 °C, with 40 % of the final energy use below 80 °C. Furthermore, analysis of streams using the traditional pinch analysis showed a location of the pinch point at 77.7 °C with a hot and cold utility target of 28.4 MW and 4.6 MW respectively. Fulfilling the entire potential of internal heat recovery estimated from pinch analysis can lead to 25 % reduction of the overall heat demand of the factory. The SSP method identified 4 feasible matches of material streams. The total heat recovery of the 4 matches summed up to around 12 GWh per year equal to yearly savings of around 2.55 MDKK with PBT on investments of maximum 2.1 years. As the matches do not generate revenue if either of the two streams is not in operation, the obtained result for the pinch matches only applies to a situation, where a contemporary factor of the processes involved is 1.

3.2 Screening of possible electrification cases

Fig. 3 presents the final energy use of each case presented above, in terms of natural gas (only relevant in BAU), electricity consumption and heat consumption. The electricity consumption represents the factories’ total electricity consumption, including e.g., office equipment, existing MVR, pumps but also new technology to cover the heat demand. The heat demand represents external heating consumption. The difference between natural gas consumption and heat demand in BAU, in Fig. 3, can be explained by part of the natural gas utilised in electricity production and the presence of boiler and distribution heat losses.

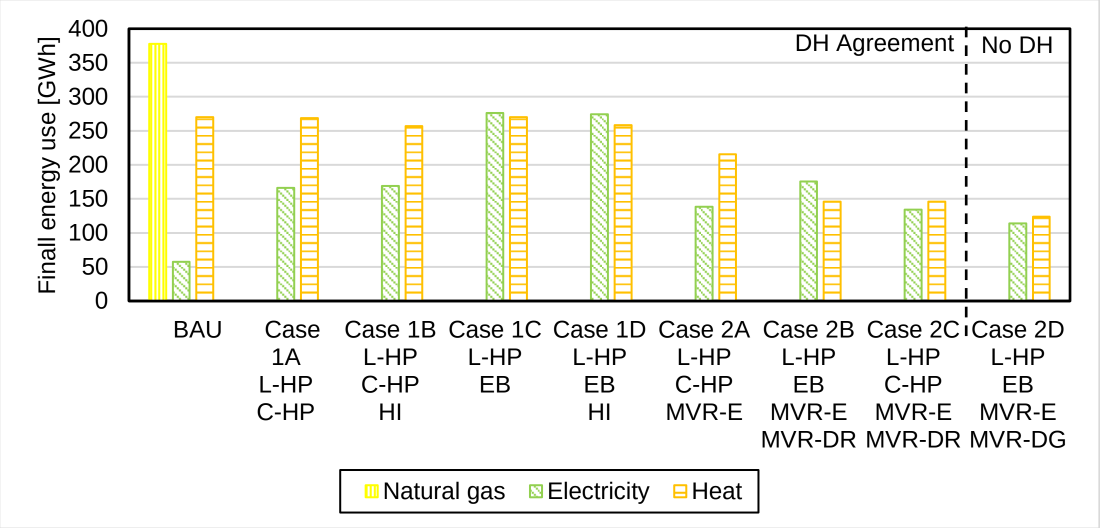


Fig. 3 Final energy use for different electrification cases in the screening phase.

The comparison of the two cases 1A and 1B, with central HP, in Figure 4, shows that heat integration from pinch analysis method does not necessarily benefit the electrification of a production site. However, in case 1C and 1D, steam is generated with an electric boiler and here the electricity consumption is lower for 1D, which includes heat integration. Generally, comparing the results of cases 1A-1D with 2A-2D illustrated in Fig. 3 shows that MVR technology reduces the heat demand significantly. Furthermore, the reduction in heat demand is largest in case 2B-D in which both evaporator and distillation processes are driven by MVR.
The distribution of electricity consumption for each technology in different cases is shown in Fig. 4.

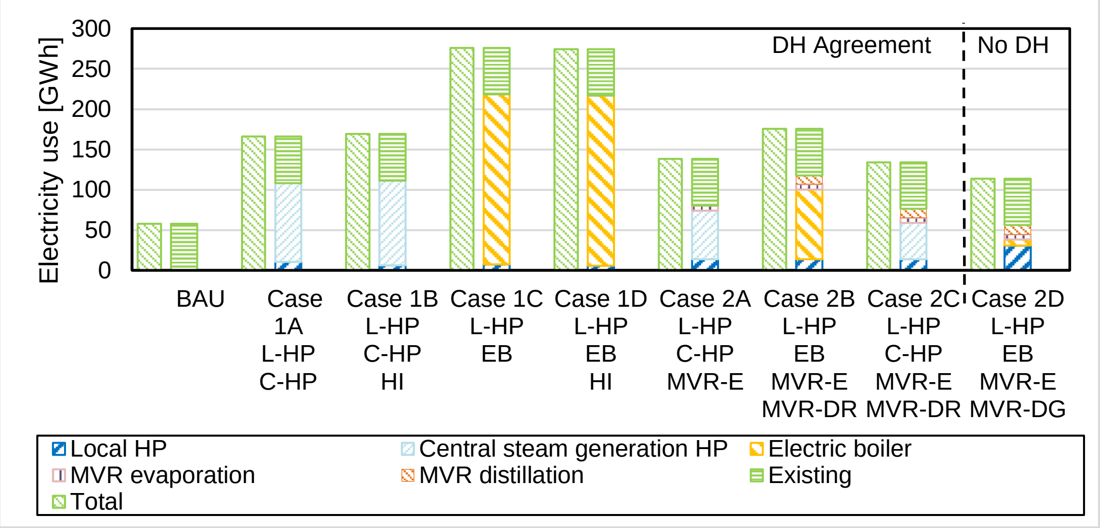


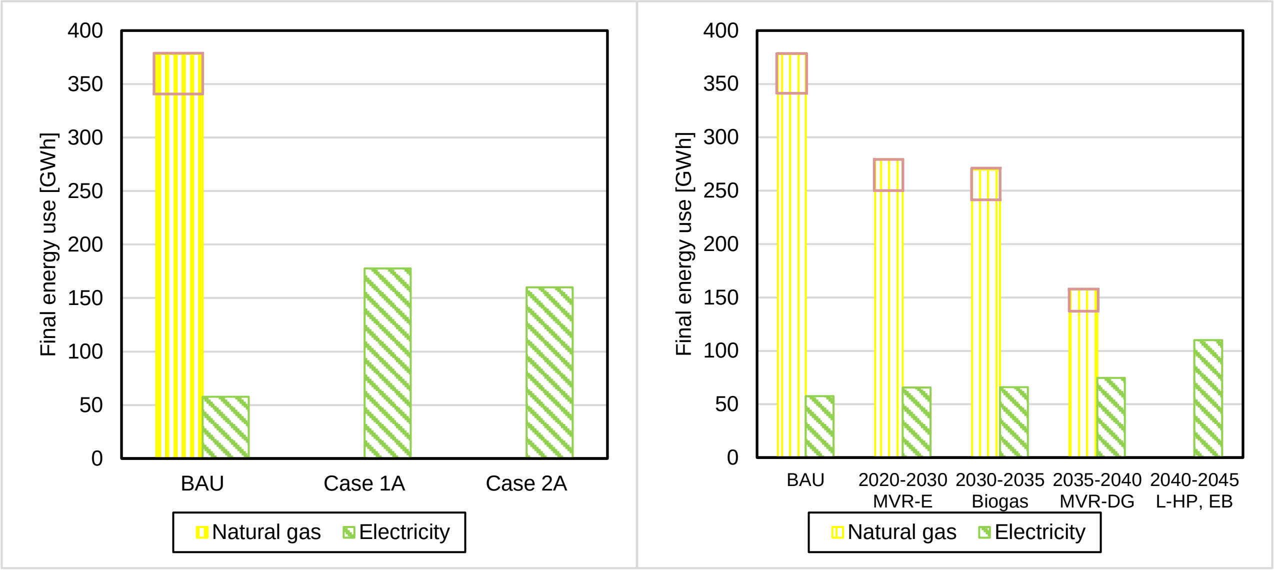
Fig. 4 Electricity consumption distribution of technologies for cases in screening phase.

It can be seen from Fig. 4 that the largest electricity consumption users are electric boilers and central steam generating HP, which are responsible for the supply of steam in the system. The cases with the lowest total electricity consumption are identified from Fig. 4 in the descending order as: 2D, 2C, 2A, 1A, 1B, 2B, 1D and 1C. In the next step, taking into consideration a quantitative parameter and the readiness level and availability of the technology and ease of implementation as qualitative parameters, the three cases 2D, 2A, and 1A are selected for further detailed analysis.

Case 2D is selected based on lowest electricity consumption, well known, and already implemented technology. The only challenge here would be leaving of district heating agreement which taken into consideration by assuming the replacement of the distillation columns not before 2030. Case 2A is selected by comparison between the two cases of 2A and 2C. As, the maturity level of the MVR distillation retrofit technology is not enough and the electricity consumption is only 4.2 GWh lower in case of 2C than 2A which might not be sufficient for covering an expectedly significantly higher investment cost. Finally, case 1A is chosen, due to low electricity consumption and low impact on existing factory processes, since it is mainly the steam generation technology that is replaced. Therefore, the investment cost is expected to be lower than the other selected cases.

3.3 Energy analysis of the selected cases

The final energy use of the two cases of 1A and 2A and case of 2D for more detailed analysis, as well as the BAU conditions is presented in Fig. 5a and Fig. 5b respectively. The outcome of the detailed analysis, presented in Fig. 5 shows different final energy use than the screening phase, which is expected, due to the consideration of more realistic heat sink and source for the HP's.



a) **b)**

Fig. 5 Energy used in different cases compared to BAU conditions in detailed electrification analysis: a) Case 1A and -2A, b) Case 2D. (Red box indicates natural gas for electricity generation).

The BAU conditions yields a yearly electricity consumption of 57.8 GWh and a yearly natural gas consumption of 378 GWh. In the cases of 1A and 2A, the natural gas combustion is removed, and the electricity consumption is increased by 207 % to around 178 GWh and 177 % to around 160 GWh per year respectively, compared to BAU. However, the total energy savings in case 1A and 2A compared to BAU reaches almost 60 % equal to a reduction of 258 GWh, and 63 % equal to reduction 276 GWh per year respectively. In addition, the comparison of case 1A with 2A in Fig. 5 shows that implementation of MVR technology on all evaporation sections reduced the electricity consumption drastically, due to the severe energy reduction per tonne of water evaporated compared to TVR. The electricity consumption in case 2A is reduced by 10 % compared to case 1A equal to a reduction of around 18 GWh per year.

For the case of 2D, as it can be seen from BAU to full electrification presented in Fig. 5b, the final energy use is reduced from 378 GWh natural gas and 57.8 GWh electricity (in total 435.8 GWh) to only 113 GWh electricity. This corresponds to a final energy use reduction of 74 %. From BAU to 2020-2030, the natural gas consumption decreases by around 90 GWh (24 %) while the electricity consumption increases by around 8 GWh (14 %). The decrease in natural gas is primarily caused by replacing evaporators and a distillation column with MVR. The electricity production also decreases, because of lower steam flow rate to the factory. From 2030-2035 the natural gas consumption decreases a bit, because of increased biogas production. The electricity consumption is unchanged, however the amount of electricity bought from the grid decreases as the biogas engine is implemented partly for electricity production. The natural gas consumption decreases further from 2030-2035 to 2035-2040 by 110 GWh (42 %), while the electricity increases by 9 GWh (13 %). The change in consumption is mainly caused by replacing the remaining distillation columns by new MVR technology. This leads to further reduction of the steam flow rate, which decreases the electricity production and boiler losses.

In the period 2040-2045 the boilers are no longer needed, as the local HP's and electric boilers are implemented to cover the remaining external heat demand. Natural gas is no longer used in combustion, which can be seen as a reduction of 158 GWh compared to previous period. The gas consumption is 158 GWh in the period 2035-2040, of this approximately 57 GWh is used to cover the boiler loss and electricity production. The electricity consumption increases by 35 GWh (47 %) because of implementation of local HP's and electric boilers.

3.4 Economic and environmental analysis of the selected cases

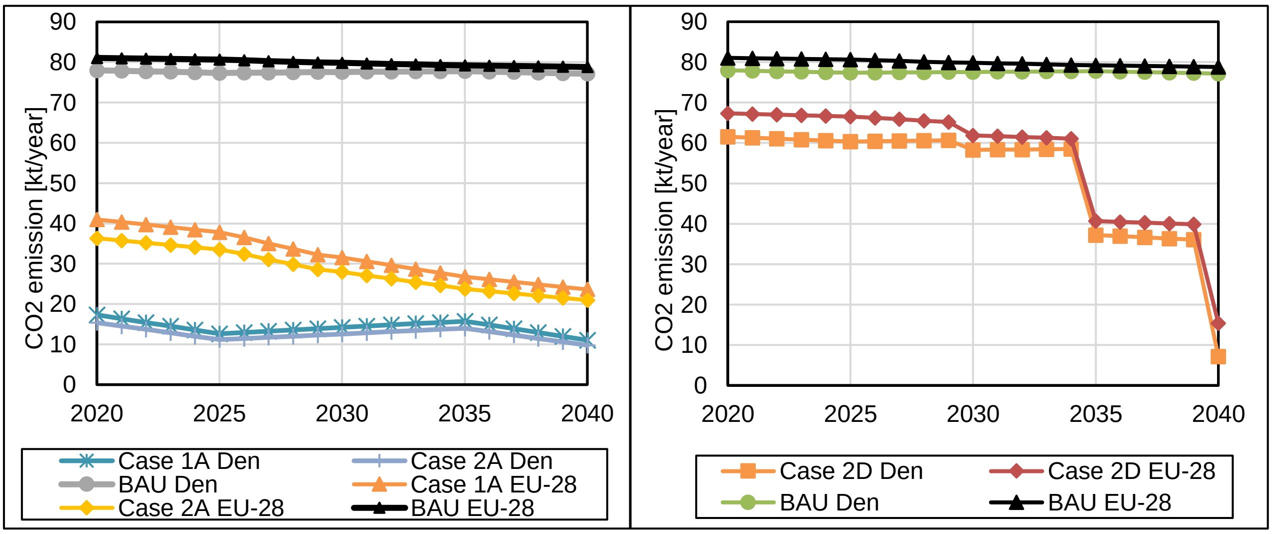
The main economic results for the complete electrification of the factory for case 1A and - 2A and different periods in case 2D are shown in Table 2.

Table 2 The main findings from the economic analysis for the selected electrification cases.

	Case 1A	Case 2A	Case 2D			
			2020-2030 MVR Evaporation	2030-2035 Biogas engine	2035-2040 MVR Distillation	2040-2045 Local HP's
TCI [MDKK]	185.5	222.5	73.9	15.3	97.4	95.6
Subsidies [MDKK]	53.8	59.7	20.5	0.0	25.8	32.0
DPT [Years]	9.7	8.2	4.6	3.4	4.1	4.7
PBT [Years]	7.3	6.2	3.7	2.9	3.4	3.9
NPV [MDKK]	232	322	201	54	250	219

Comparison between the two cases of 1A and 2A shows that case 1A has lower overall investment with a TCI of almost 17 % than case 2A. However, the subsidy from energy savings in case 1A are somewhat 10 % lower in the first year of operation than in case 2A, which indicates a higher yearly revenue in terms of energy savings of around 24 GWh in case 2A. Over an assumed lifetime of 20 years, the NPV of the case 2A shows superior economic tendencies compared to case 1A, as the net present value of the case is almost 100 MDKK higher than case 1A equal to around 40 %. Moreover, both the simple payback time and the discounted payback time is more than a year shorter for the case 2A, which highlights the importance of a large final energy use reduction, especially towards the end of the NPV analysis. Towards the end of the lifetime of the electrification technologies, the yearly earnings increase based on the natural gas price to increase more relative to the electricity price. This explains a significantly higher yearly savings in case 2A compared to 1A.

For the case of 2D, the first thing to notice is that all project steps have positive NPV, which means that the projects are economically feasible. The other main economic evaluation parameter is the PBT, which for all periods are less than 4 years and even less than 3 years for the project with biogas engine. The TCI for the four projects combined is 282 MDKK. It is important to note that the NPV for the different project are made by comparing the cash flow before and after the implementation, e.g., BAU to 2020-2030 and 2020-2030 to 2030-2035. Therefore, the NPV cannot be summarised for all the project steps, since each project does not run its full lifetime before another implementation is made.
By fully replacing the combustion of natural gas with electricity driven technologies, it is expected that the CO_2 footprint of the factory impacted to a large degree. Fig. 6 shows the annual CO_2 emissions of cases 1A and 2A for Denmark (Den) and the European union 28 (EU-28).



a) **b)**

Fig. 6 Yearly CO2 emission for selected electrification cases for Denmark (Den) and the European union 28 (EU-28): a) cases 1A and 2A, b) 2D.

Fig. 6 shows that the CO_2 emissions over the 20 years of the lifetime decreases in both cases for both Denmark and UE-28. As it can be seen from Fig. 8, the CO_2 emissions over the 20 years of the lifetime decreases in both cases for both Denmark and UE-28. In 2020, the CO_2 emissions is significantly higher (about 135%) for UE-28 than Denmark, due to varying electricity generating technologies. This trend is continuously decreasing for UE-28, whereas for Denmark increases slightly from 2025 to 2035. In 2039 the reduction of CO_2 emission for the two cases 1A and 2A compared to BAU is found to be about 68 kt (85 %) for the two Danish cases compared to the reduction of around 56 kt (70 %) for and EU-28.

For the case of 2D, it can be seen from Fig. 6, that after the first implementation in 2020 the total emissions drop by 13-17 kt/year. In 2030, by introducing the biogas engine, the CO_2 emissions drops additionally 2 kt/year. In 2035, by replacement of new MVR with the distillation columns, the yearly emission reaches to 40 kt/year below BAU in the same year. In 2040, by full electrification of the factory the yearly CO_2 emission is only about 7-15 kt/year from electricity consumption. This gives a reduction of more than 90% and 80 % for Denmark and EU-28 respectively.

In general, between the three selected cases, case 1A would probably be deselected since it had a larger PBT than 2A with almost the same technologies. This leaves two options, case 2A if DH agreement should continue or case 2D if the DH agreement is ended. Case 2A had a PBT of 6.2 years, which in many companies are considered too long. However, more factors play a role in this specific project. First, the NPV is of considerable size, 322 MDKK. Secondly electrification may well be a necessary step to take, both in an environmental perspective but also from political perspective, if Denmark wishes to achieve net-zero emission before 2050.

Lastly it can improve the ’green profile’ of the company which is of increasingly importance for companies nowadays. Besides the PBT, the central HP technology is also challenging for case 2A. It has yet to be implemented at an industrial site. Case 2D seems to be the most promising electrification proposal given that all the implementation towards full electrification in 2045 have a positive NPV and a PBT in the range 2.9-3.9 years. All the technologies are known and has been implemented elsewhere. Positively for case 2D is also the way of electrification since it is not dependent on a central steam generation technology and is solely based on local technology replacement.

4. Discussion

For the electrification study, the high process temperatures above 90 °C are challenging with respect to availability, when seeking to supply heat under economic feasible conditions. Selection of the cascade heat pump with a multi-stage R-718 cycle for steam generation, is a theoretic technological solution presented by [8,16]. Under BAU conditions, the steam supply varies to the processes besides the base load of the factory. Some processes such as autoclavation take up a considerable amount of steam over a very short period, as the process can be considered batch process. The steam consumption by the autoclaves alone causes the general steam demand for the factory to increase by 5 tonne per hour. By having heat pumps supplying heat with a low temperature difference between water and refrigerant in the condenser while having a large amount of water in the sub-atmospheric tank, one could argue that the large fluctuations in steam demand could be challenging. A method of meeting the high fluctuations in steam demand could be to implement a run through buffer tank of steam at the steam pressure needed, thus emptying this when the fluctuations take place. However, this issue should be studied more into detail, as this might become a physical bottleneck for the central steam production using heat pumps and vapour compressors in a large-scale operation.

Furthermore, the effects of pressure losses have not been considered in this study. it was assumed that the existing steam piping system could be reused when the pressure was reduces from 6 bar(g) to 2 bar(g). However, when the pressure is reduced, the density decreases, which ultimately require a higher velocity in the pipes to deliver the same amount of steam energy. Therefore, a trade-off between compressor electricity consumption and investment cost for piping would determine if the existing pipes should be reused.

In addition, Economic analysis shows that the electricity and gas prices play a crucial role in electrification of industrial processes. In addition, the study also shows the current importance of governmental support to make electrification projects economic feasible. Without the assumed subsidy, the NPV would be reduced and PBT increased, overall reducing the likelihood for the required investment to happen.

5. Conclusions

This study investigated the potential for energy and economical savings in electrifying industrial processes of low-to-medium temperature, by drawing up concrete scenarios in a case study, to cover the energy demand at CP Kelco, a large-scale factory producing pectin and carrageenan. The Study showed that with full electrification of CP Kelco, the final energy use is reduced by approximately 69% and CO2 emission by 90 % in 2045. In addition, the analysis also showed that it is not always beneficial to perform a pinch analysis and

implementing a heat exchanger network before initiating an electrification plan. Furthermore, it was clear that other factors might constrain the electrification possibilities. Specific to CP Kelco, a district heating agreement stood out as a limitation for successful electrification with heat pumps. This is an important lesson learned, which other companies can benefit from, as excess heat should preferably be utilised within the factory boundaries. The electrification may well be a necessary step to take both in an environmental perspective but also from political perspective if Denmark wishes to achieve net-zero emission before 2050. In addition, it can improve the ’green profile’ of the company which are of increasingly importance for companies nowadays.
The work has led to insight in fields of the electrification, impacted by barriers for successful investments. It was found that the electricity to natural gas cost ratio plays key role in successful electrification if the BAU conditions are based on natural gas combustion. Moreover, the total investment cost of electrical driven technologies such as heat pumps and MVR tend to be high, which might become a challenge in the transition period, if the BAU conditions are already energy efficient.

Nomenclature

Abbreviations:

BAU	Business As Usual
C − HP	Central Heat Pump
COP	Coefficient Of Performance
DH	District Heating
DPT	Discount Pay Back Time
EB	Electric Boiler
HI	Heat Integration
HEN	Heat Exchanger Network
HP	Heat pump
L − HP	Local Heat Pump
MVR − E	Mechanical Vapour Recompression - Evaporation
MVR − DG	Mechanical Vapour Recompression – Distillation Grass Root
MVR − DR	Mechanical Vapour Recompression – Distillation Retrofit
NPV	Net Present Value
PBT	Pay Back Time

Greek and Roman Letters:

Δ	Absolute difference
A	Area, m^2
h	Specific enthalpy, kJ/kg
k	Model constant
$\dot{m}$	Mass flow rate, kg/s
P	Power, kW
$\dot{Q}$	Heat rate, kg/s
T	Temperature, °C
U	Overall heat transfer coefficient, W/(m^2 K)
x	Size

Subscripts and superscripts
is isentropic

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