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Opportunities of high temperature heat pump integration in various industrial subsectors

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Abstract—Industrial electrification is an important step on achieving net-zero in industry. For several industrial subsectors in Canada, a significant portion of the energy input is consumed in fossil fuel boilers. An interesting solution is the replacement of the boiler with a high temperature heat pump (HTHP) capable of delivering the required process heat. The efficiency of a HTHP being closely dependent on the waste heat temperature levels, this effect is also studied. The results show that electrification of boilers by HTHPs being supplied with waste heat at 29°C leads to energy savings of 11%, 14% and 38% in the petroleum refining, pulp and paper and food and beverage subsectors respectively. These numbers can significantly increase when part of the heat can be obtained through heat recovery alone and/or heat pumping from higher-temperature waste heat, which is expected to always be the case, although in proportions that are site-specific. One challenge in making HTHP projects cost-effective is the higher electricity cost compared to fossil fuels. This issue is partly addressed through carbon pricing mechanisms and a high coefficient of performance (COP).

Keywords-component; high temperature heat pump (HTHP); electrification; waste heat recovery (WHR); mechanical vapour recompression (MVR)

I. Introduction

The desire to reach net zero by 2050 presents the need for bold change in industry. For example, fossil fuel boilers are commonly used to provide steam in industry. However, as the need to decarbonize increases, electrified solutions are becoming strong candidates to reduce the utilization of this equipment. This is particularly true given the lower temperature requirements of steam-heated processes, most of which operate below 200°C, with a significant portion operating below 150°C.

Additionally, research efforts have been directed towards optimizing heat exchanger networks to minimize energy consumption and cater to the temperature requirements of various industrial processes [1], [2]. The pinch method, originally developed for heat exchanger networks, has also been successfully applied to cooling water networks [3] and is especially relevant for general process integration in the industrial sector [4].

Replacing fossil fuel boilers with electric boilers is becoming less attractive due to the limited availability of renewable electricity and its higher cost compared to fossil fuels. Heat pumps, however, offer a promising solution. They have been extensively studied and are employed in various applications for renewable heating and/or cooling. The opportunities for heat pump technology are expanding, and advancements are being made in increasing the temperature limits of heat pump systems.

One area of growing interest is the decarbonization of industrial low/medium-temperature processes heat using heat pumps. Recent studies include systems well above 100°C [5], [6], [7], [8]. Recently, the use of steam-generating heat pumps, which operate with supply temperatures ranging from 120 to 350°C, has been explored [6]. The study found that closed-loop systems can produce sensible heat up to 250°C, while open-loop systems, such as mechanical vapour recompression, can achieve temperatures up to 350°C. By using a high boiling point refrigerant in a closed-loop system, it may be possible to produce low-pressure steam. Successive compression stages could then be utilized to deliver steam at the desired pressure.

The current study looks at replacing fossil fuel boilers in three different industrial subsectors: pulp and paper, petroleum refineries and food and drinks. The opportunities and individual challenges for each subsector are covered.

II. Methodology

The estimation of the fossil fuel energy consumed for each sub-process is needed before being able to do any form of HTHP integration analysis. This sub-process energy mapping allows to establish the temperature range and process type, as well as the specific energy intensity, for the reported fossil fuel consumption. For the current study, it is considered that all the energy going to boilers or similar temperature level processes would get replaced by HTHPs.

A. *Energy mapping of the industrial subsectors*

The energy mapping of the industrial sub-processes is based on the totals provided by the federal energy and emissions inventories of the Office of Energy Efficiency [9] and Environment and Climate Change Canada [10]. The breakdown between sub-processes for the refinery subsector is based on the work of the Department of Energy as well as the book ‘’ Energy Analysis of 108 Industrial Processes’’[11]. The pulp and paper sub-process breakdown is based on the work of [11] and internal simulations using commercial software. The food and drink sector energy breakdown is based on [11] as well as [12]. The data is extracted based on the six digits North American Industrial Classification System (NAICS) codes. The food and beverage industrial subsector is covered for the following: Meat (NAICS: 311611, 311614, 311615), Dairy (NAICS: 311515), Fruit and vegetable (NAICS: 311410, 311420) and Breweries (NAICS: 312120). For the pulp and paper industrial subsector: (NAICS: 3221). For petroleum refining: (NAICS: 324110).

B. *Description of HTHP scenarios*

Different scenarios are considered given the differences between each subsector.

- Scenario 1 considers supplying steam below 200°C using an MVR to upgrade heat supplied by a HTHP using a 5°C waste heat source.
  - For the HTHP : COP=2 ; 1 PJ of electricity + 1 PJ of extracted heat = 2 PJ steam
  - For the MVR: COP=4 ; 1/4 x (2 PJ steam) = 0.5 PJ of electricity + 1.5 PJ steam = 2 PJ compressed steam
- Scenario 2 considers supplying steam below 120°C supplied by a HTHP using a 5°C waste heat source.
- Scenario 3 considers supplying steam below 200°C using an MVR to upgrade heat supplied by a HTHP using a 29°C waste heat source.
- Scenario 4 considers supplying steam below 120°C supplied by a HTHP using a 29°C waste heat source.

For this study, scenarios 1 and 3 will be applied to the petroleum refinery and pulp and paper subsector while scenarios 2 and 4 will be applied to the food and drink sector.

These generic scenarios are known to be suboptimal in many ways. For example, the electricity requirements could be much lower in processes requiring lower lifts (e.g.: hot water production, pasteurization, material preheating, etc.). The scenarios developed allow a conservative COP estimate of each subsector given the high-level analysis and the uncertainty surrounding it. In general, they overestimate the electricity demand and underestimate the COP that would be obtained through well-integrated HTHP designs. Such designs are site specifics and are not covered in this paper.

III. Results and Discussion

Each subsector is presented in the following sections. First, the baseline energy consumption is established. Then, two scenarios are considered for heat pump integration in the industrial sector to replace fossil fuel boilers.

For the first heat pump scenario, it is considered that heat pumps can be supplied with waste heat in the form of water at 5°C, representing environmental heat or highly degraded waste heat. It is considered that the energy supplied by the boilers can be entirely replaced by heat pumps.

For the second heat pump scenario, it is supposed that there is sufficient waste heat to be able to supply the HTHP with water at 29°C. For petroleum refining as well as the pulp and paper industrial subsectors, it is considered that an MVR is needed to supply the necessary steam to the process.

A. *Petroleum refining subsector*

For the petroleum refining industrial subsector, over 290.7 PJ of energy is consumed, with electricity only representing 21.3 PJ. Refinery fuel gas is the largest fraction of energy consumed at 145.4 PJ and is a by-product of the transformation of crude oil into various petroleum products. Figure 1 shows the sub-process energy breakdown for this subsector.

For the first heat pump scenario, it is considered that an MVR will be needed on top of the HTHP. It is assumed that all the fossil fuels, except the refinery fuel gas, the petcoke consumed at the catalytic cracker and the coke on catalyst, can be eliminated. It is also considered that the refinery fuel gas will continue to be used for the SMR and other furnace needs as it is a by-product of the process. Electrifying the boiler with a HTHP + MVR represents an increase of annual electricity consumption of over 46.7 PJ. Figure 2 shows the updated sub-process energy breakdown for this HTHP scenario. Further analysis is needed in order to better understand what other uses of the 145.4 PJ of refinery fuel gas such as additional gas treatment or cryogenic separation steps to recover specific by-products instead of flaring it all. The potential surplus of refinery gas is currently viewed as an obstacle to the complete electrification of furnaces (though obviously not all of it could be done using HTHPs). The use of petcoke should also carefully be examined.

For the second heat pump scenario, the same fossil fuels are substituted by electricity supplying a HTHP+MVR, but with higher-grade waste heat available for recovery (WHR). This case is shown in Figure 3. This scenario using WHR and HTHP+MVR leads to a 4.2 PJ reduction in energy consumption when compared to the initial HTHP+MVR scenario and a 32.8 PJ reduction in energy consumption when compared to the baseline.

The petroleum refining industrial subsector presents a lot of uncertainly related to the decarbonization pathways. A recent study explores the decarbonization options for global petroleum production. They mention that within the refining process, energy efficiency and waste heat recovery and utilization will be necessary to reach the net-zero goals [13]. Commercial solutions for heat pumps are available [14].

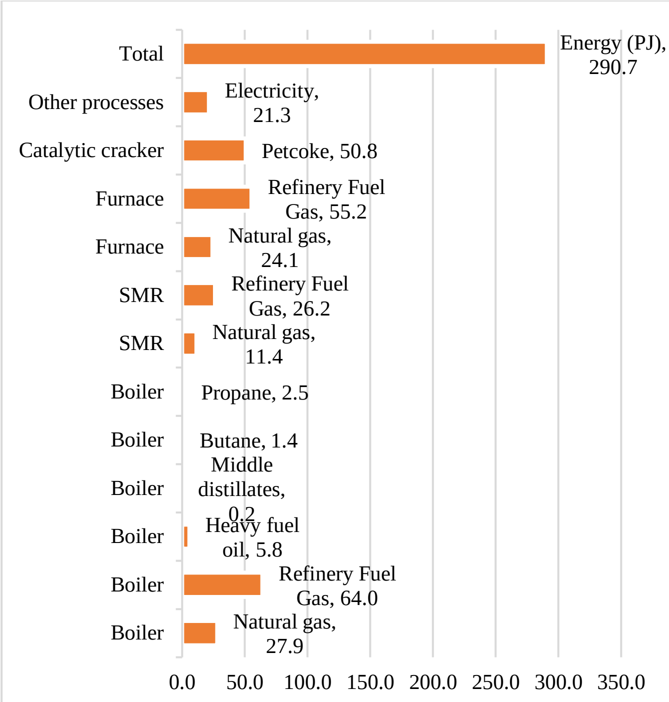

Figure 1: Baseline energy consumption for the petroleum refining subsector – estimations from process energy mapping performed by the authors

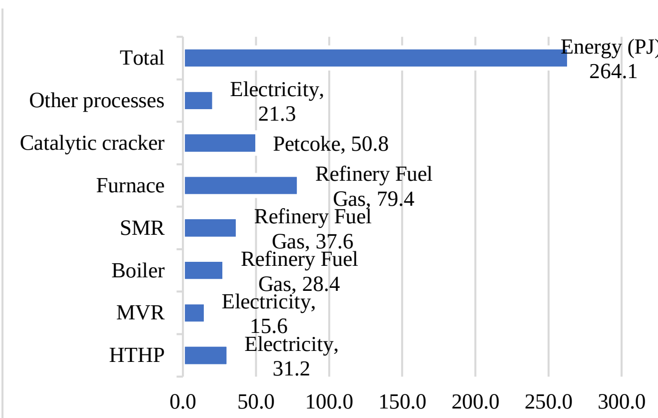

Figure 2: HTHP with 5°C waste heat source for the petroleum refining subsector – only excess refinery fuel gas going to boilers

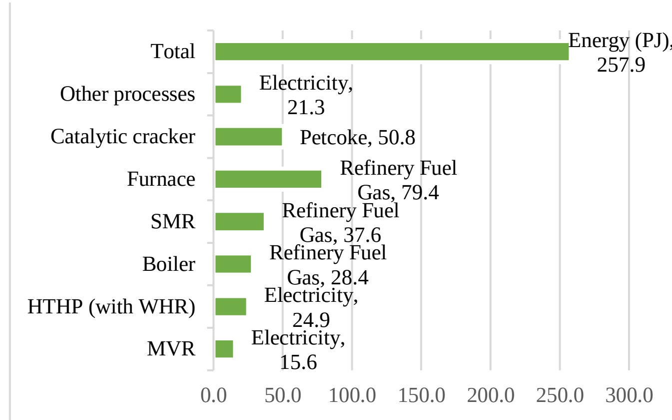

Figure 3: HTHP with 29°C waste heat source for the petroleum refining subsector – only excess refinery fuel gas going to boilers

B. Pulp and paper subsector

The pulp and paper subsector consumes over 561.3 PJ of energy with the largest fraction being bioenergy in the form of spent liquor totalling 215.9 PJ. Electricity consumption is 136.9 PJ. The rest of the bioenergy, 102.0 PJ, is considered to be consumed in the power boilers for heat and electricity production. The remaining energy represents the use of fossil fuels. The production of steam and electricity from biomass could limit the implementation of HTHP in this sector as they are linked to local power purchasing agreements. For this reason, the reported potential bioenergy savings in this study is likely overestimated. The interactions of these purchase agreements should be modeled in a more detailed study at a plant level to assess the true technoeconomic potential of heat pumps. This has not been considered in the scope of this work. Figure 4 illustrates the sub-process energy breakdown.

For the first heat pump scenario, it is considered that the fossil fuels and the bioenergy supplying the power boilers can be entirely replaced by heat pumps using the HTHP+MVR, supplied with waste heat in the form of water at 5°C. Figure 5 shows the updated sub-process energy breakdown for this scenario.

For the second heat pump scenario, it is considered that the fossil fuels and the bioenergy supplying the power boilers can be electrified using the HTHP+MVR with WHR. Figure 6 shows the updated sub-process energy breakdown for this WHR scenario. For a total energy consumption of 482.2 PJ, this represents a 14.1% decrease in baseline energy consumption. When compared to the initial HTHP+MVR case, the increased WHR leads to a 15.0 PJ decrease in electricity consumption.

A similar study for the US, indicates that 41% of energy savings can be obtained by integrating HTHP in the pulp and paper sector [12]. It is important to note that it was only the kraft process that was modelled. The same study considered that an MVR isn't needed as the recovery boiler supplies steam for the higher temperature users i.e., over 120°C. In the current study, the sub-process energy breakdown considers all pulp and paper activities including kraft mills. Recently, in Italy, an industrial

HTHP project in a pulp and paper mill has been announced. For this project, the heat source for the large heat pumps is humid air and wastewater from a paper mill, which is integrated into a single water loop that usually ranges from 7°C to 12°C (but could arguably be better designed at higher temperatures). The HTHP first raises the temperature 114°C at 1.5 bars of absolute pressure and then a steam compressor escalates the steam to 170°C at 3.5 bar,abs. [15]. This announcement is in line with a joint paper between the European Heat Pump Association (EHPA) and the Council of European Paper Industries (CEPI) which states that HTHPs can provide heat up to 200°C and efficiency electrify this industrial subsector while providing 50% energy savings for paper drying [16].

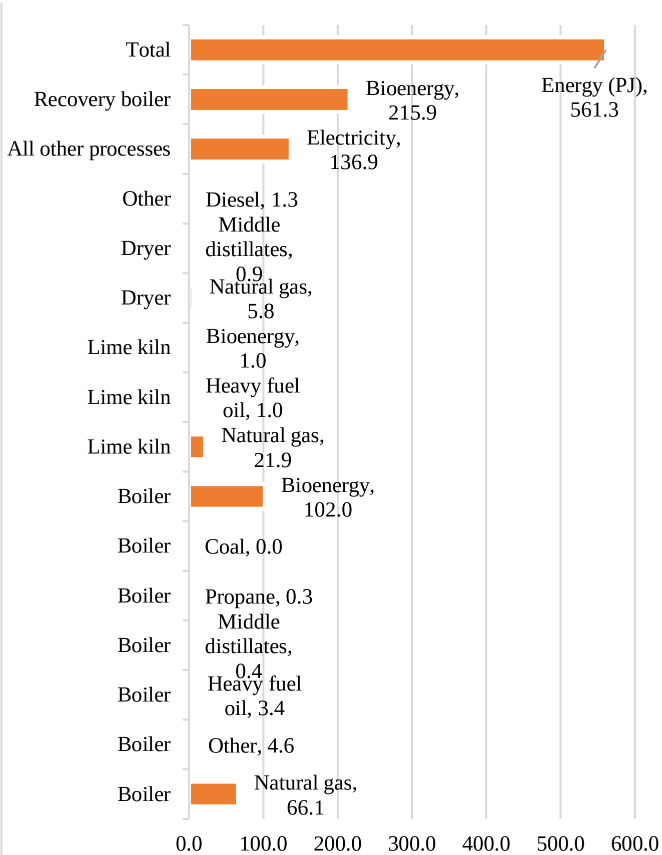

Figure 4: Baseline energy consumption for the pulp and paper subsector

C. *Food and beverage subsector*

The meat, dairy, breweries and fruits and vegetables subsectors are grouped together as the food and beverage subsector. Over 47.1 PJ of energy is consumed with electricity representing only 15.0 PJ of the demand, the rest is the use of fossil fuels. Figure 8 presents the sub-process energy breakdown for the food and beverage subsector.

For the first heat pump scenario, it is considered that all the fossil fuel consumption can be electrified. The scenario for this subsector considers that the HTHP alone without an MVR is sufficient for the process needs, which tend to be at lower temperatures. Figure 7 shows the updated sub-process energy breakdown for this scenario. Compared to the baseline energy consumption of over 47.1 PJ of energy, this scenario leads to complete electrification using only 31.5 PJ of electricity. This is an increase of over 23.6 PJ of electricity but leads to energy savings of over 15.6 PJ or 33% of the initial energy consumption.

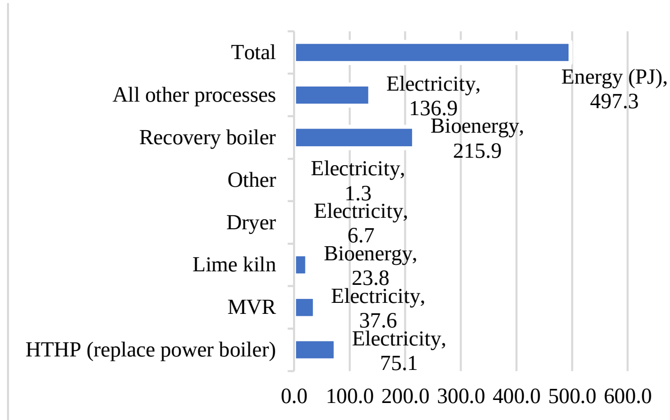

Figure 5: HTHP with 5°C waste heat source scenario for the pulp and paper subsector

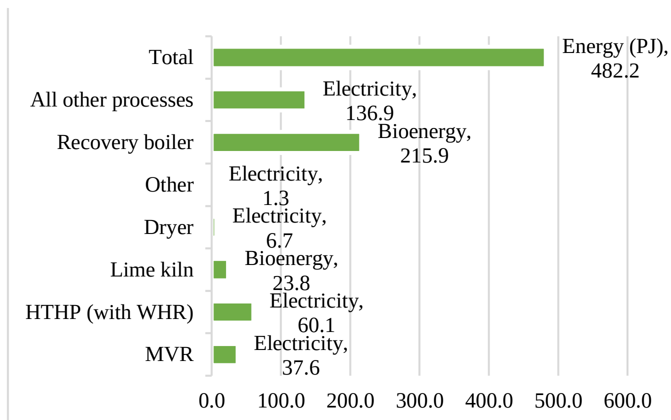

Figure 6: HTHP with 29°C waste heat source scenario for the pulp and paper subsector

Figure 9 shows the sub-process energy mapping of the subsector, for the second heat pump scenario when a HTHP with WHR is used to decarbonize the boilers. Compared to the baseline energy consumption, this scenario of WHR leads to complete electrification using only 29.2 PJ of electricity. This leads to energy savings of over 38.0% when compared to the baseline scenario or 7.3% energy savings when compared to the initial HTHP scenario.

These results are in line with other similar reports on heat pump integration in the food and beverage sector. Similar results are obtained in [17] looking at the same industrial subsector in the US. Indeed, for the dairy sector, the energy-saving potential of using HTHP can be as high as 65% for a new facility and 62% for retrofitting an existing facility with, given as an example, the decarbonization of a site in Trondheim which led to energy savings of 54% [18]. They report on the use of thermal energy storage tanks and fully integrating building heating and cooling requirements in the HTHP system. Similar concepts have been proposed for the meat processing sectors as well by using thermal tanks that allow flexibility in operation over a 24-hour period [19]. Various projects in breweries report roughly 40% energy savings by utilizing total process integration with the building utilities [20], [21].

D. Discussion

To electrify these subsectors efficiently there exists a number of barriers to overcome. The most significant challenges and barriers have been reported by [5], [6], [7], [8], [12], [17]. Some of these barriers are highlighted here. The first one is the relatively high electricity cost compared to the natural gas price. The Canadian energy prices are also lower than that of the European market. Since price is a driver for energy efficiency projects, they won't naturally happen given low fossil fuel prices. Coupling this to the higher cost of a HTHP system, a well-structured policy and/or program is needed to stimulate project implementation. Alternatively, aggressive carbon pricing could also contribute achieving similar results. The second main barrier is the need for tailored projects for each industrial site which increases the price of the HTHP project. Coupling this with the higher cost of electricity, it is challenging to obtain an acceptable return on investment for HTHP projects replacing boilers under current market conditions. The third main barrier is the lack of stakeholder engagement and supplier development in Canada and in the US. Finally, the fourth barrier is that labor shortages cannot be ignored as skilled labor is needed to install and ensure the reliability of these systems.

Another important consideration is investments in additional renewable electricity generation, transmission and distribution to supply these industrial HTHP projects on top of what will be needed to decarbonize the electricity grid. Regulatory bodies must work together to ensure that the industrial sector can be decarbonized entirely. Even with some fossil electricity production, HTHPs still emit less than electric boilers. This way, industrial electrification projects could happen as new renewable energy projects are connected to the grid.

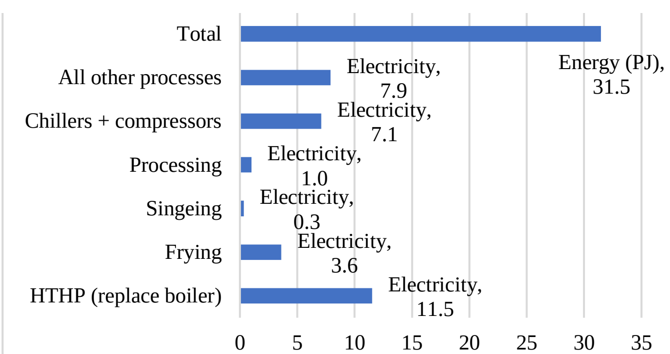

Figure 7: HTHP with 5°C waste heat source scenario for the food and beverage subsector

Figure 8: Baseline energy consumption for the food and beverage subsector

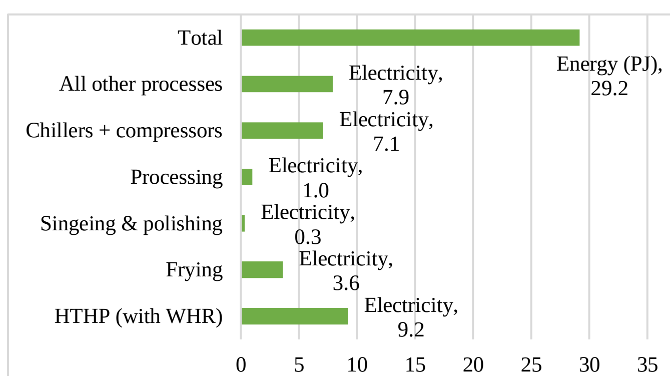

Figure 9: HTHP with 29°C waste heat source scenario for the food and beverage subsector

IV. CONCLUSION

The current study shows that it is possible to efficiently electrify steam production in the pulp and paper, petroleum refining and food and beverage industrial subsectors with the use of HTHPs. The replacement of fossil fuel boilers by a HTHP system with a 5°C waste heat stream would lead to an increase of the electricity use of 170.9 PJ (47 TWh) and would save over 148.1 PJ of fossil fuels and 102.0 PJ of bioenergy. This represents the absolute minimum COP of 1.5 that can be obtained by replacing fossil fuel boilers, where none of the heat can be obtained through heat recovery or heat pumping from higher-temperature waste heat. If the HTHP systems were instead supplied with 29°C waste heat — a more realistic but still conservative estimate — only 147.4 PJ (41 TWh) of additional electricity would be needed to achieve the same savings in fossil fuels and bioenergy. This would result in a COP of 1.7. The electricity consumption of the HTHP systems could be further reduced through heat recovery, operational improvements, technological advancements, and integrated configurations where heat is supplied at lower temperatures for processes that don't require steam (such as hot water production, pasteurization or material preheating). Additionally, using higher-temperature waste heat when available could further lower electricity demand.

A well thought-out HTHP integration plan will seek tailored projects that improve payback by maximizing heat recovery and minimizing temperature lifts, ensuring minimal electricity consumption at the expense of a more complex design phase.

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