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A Systematic Electrification Approach: Electrifying Natural Gas Processing for a Net-Zero Future

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This work presents a systematic approach to evaluate heat electrification as a decarbonization strategy for the chemical industry, using a natural gas processing plant as a case study. Heat pumps and electrode boilers are primarily selected as electrified technologies to replace conventional ones. Electrified technologies data was collected through a literature review to facilitate the evaluation of their technical feasibility. Pinch technology was employed to optimize energy utilization within the plant to generate minimum utilities needed as a base point for electrification. Multiple scenarios were adopted within the case study including conventional heating utilities both on-site and off-site, 100 % electrified heating systems, and electrified solutions using only heat pumps. Composite Curves generated from Pinch technology were used to systematically place the electrified technology based on heat loads and temperature targets. The electrified case study resulted in an 83 % reduction in minimum heating requirements, using heat pumps to leverage waste heat that would otherwise require cooling utilities. Despite the significant reduction in carbon dioxide (CO_2) emissions and over 30 % decrease in energy consumption, electrification incurred higher Total Annualized Cost (TAC). Minimum Marginal Abatement Cost curves (Mini-MAC) were used for a cost-effective comparison of electrification options. This study provides general guidelines and a framework for assessing and implementing electrification as a pathway towards a sustainable, net-zero future for industrial processes.

1. Introduction

In 2023, global energy-related CO_2 emissions from energy sources rose by 1.1 %, climbing by 410 Mt metric to hit an unprecedented 37.4 Gt metric (IEA, 2024). This trend poses a challenge to global efforts to align with the global climate goals set in the Paris Agreement to reduce emissions and keep the increase in average global surface temperature well below 2 °C.

In 2021, the chemical sector's worldwide emissions amounted to roughly 925 Mt of CO_2 (McKinsey & Company, 2023), ranking it among the top three emitting industries. According to the Net Zero Emissions by 2050 (NZE) Scenario, CO_2 emissions are projected to decouple from production in the next few years, with a target of 18 % reduction in CO_2 emissions by 2030 compared to 2022 levels, despite an increase in production (IEA, 2023).

The chemical industry's diversity presents challenges to having a universal solution to decarbonize it; however, one common source of emissions across different industries is industrial heat, which usually accounts for over half of the industrial energy demand, contributing to a large portion of its emission. Decarbonizing industrial heat presents numerous opportunities for innovation, one of which is electrification—to substitute fossil fuels with Renewable Electricity (RE). The recent research by Selleneit et al. (2019) underscore electrification's potential to enhance industrial utilities' efficiency and integrate renewable energies effectively. Their findings support the pursuit of electrification strategies as a pathway toward decarbonization in the chemical industry. Electrification could be indirect through using e-fuels and e-feedstock or direct by powering heat pumps and electric steam generators for process heating purposes. Advanced electrified technologies are grouped by how they generate heat, such as electromagnetic, microwave, and plasma technologies (Department of Energy, 2015). Current heat recovery practices often fail to efficiently utilize low-temperature waste heat, resulting in significant energy losses (Liu et al., 2017). Heat pumps are gaining traction as a promising electrifying technology because they address the issue of repurposing heat that otherwise would be wasted. Traditionally, heat pumps were used for temperatures lower than 100 °C. However, newly developed High-Temperature Heat Pumps (HTHP) can now

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reach temperatures up to 200 °C. Zühlsdorf et al. (2019) highlighted that these high temperatures are achieved through the optimal selection of a suitable refrigerant. Arpagaus et al. (2018) discussed that maintaining a temperature difference (T_{lift}) of 70 °C or less is crucial to achieving a reasonable coefficient of performance (COP). Electrode boilers offer a well-established technology for steam generation, boasting high efficiency and readiness levels, with a temperature range of 100-350 °C (Zaporozhets, 2023).

In the recent study of Bogdanov et al. (2021), it is demonstrated that transitioning to a fully sustainable and renewable energy system by 2050 is feasible. Through intensive electrification and sector integration, significant reductions in CO_2 emissions are achievable. Current studies on electrification focus on electrified technologies maturing, for instance, the development of an electric furnace as a replacement for steam cracking announced by Dow and Shell (DOW, 2020). Additionally, the development of new processes through indirect electrification, such as the work of Chen et al. (2019), uses electricity to synthesize alternative feedstock with higher energy content in methanol production. Usually, the studies are concerned with specific applications rather than providing a unified approach applicable across a wide range of industrial processes. This study aims to address this gap by assessing the electrification of industrial heat and generating guidelines for a systematic approach to electrification, targeting plants with intensive energy consumption. By examining the potential of electrification to reduce emissions and enhance efficiency in industrial processes, this research seeks to contribute to the development of comprehensive decarbonization strategies for the chemical industry.

2. Methodology

The work of this paper utilizes Pinch Technology for heat integration to identify the minimum required heating and cooling demands and to select suitable utilities to meet them. Process stream data of selected plants are extracted for Heat Integration. The process involves screening available heat-supplying technologies and determining the suitable ones. Once the conventional utility system is established, electrified technologies are matched based on the technology's temperature range and its efficiency to supply the required heat loads. The Grand Composite Curve (GCC) generated from Pinch Technology is used to screen and place available utilities. The cost, efficiency, and energy consumption parameters were identified from the literature review, along with energy prices and fuel selection.

Capital and operating costs are calculated and annualized to generate the Mini-MAC for a cost comparison of the electrification scenarios based on the cost per ton of CO_2 reduced.

Technology Readiness Level (TRL) was considered a key parameter in the selection of applied electrified technologies as it facilitates the realistic feasibility of electrification. Therefore, electrode boilers and HTHP are considered in the placement of the steam boilers and conventional heating utilities.

2.1 Pinch Technology

As the Pinch point is identified, cold and hot streams are matched according to the constraints imposed by it. The minimum temperature difference assumed for this study is 10 °C for maximum heat recovery. A temperature-enthalpy diagram is constructed which is the Composite Curve (CC). It combines the temperature profiles of the hot and cold streams extracted from the process of interest, illustrating the total heat transfer requirements of the process and identifying the Pinch Point, which is the point where the hottest temperature of the cold stream matches the coldest temperature of the hot stream. The Composite Curve provides a visual representation of the heat transfer requirements and opportunities for heat recovery within the process.

Extending the concept of CC, the Grand Composite Curve (GCC) includes additional information on the heat recovery zones, utility targets, and heat transfer requirements, allowing for easy identification of utilities needed. This enables a systematic evaluation of the advantages of substituting traditional equipment with electrified alternatives. Multiple constraints are set by the Pinch Technology such as no cooling utilities above the Pinch and no heating utilities to be used below the Pinch. These constraints guided the placement of electrified technologies. For example, the HTHP has been placed across the Pinch to accommodate its system of leveraging waste heat from below the Pinch to be used as a heating source above it.

2.2 Energy system and cost

Steam was used as the main heating utility, with steam specifications shown in Table 1 (Smith, 2016). The conventional steam boiler and electrode boiler were assumed to have efficiencies of 80 % and 98 %, respectively. The HTHP is based on a reversed Carnot Cycle and consists of two heat exchangers, a condenser and an evaporator, a compressor, and an expansion valve. The heat pump's performance is based on COP.

$$COP = \frac{T_{sink}}{T_{sink} - T_{source}} \tag{1}$$

In Eq.1, T_{sink} is the target temperature of the heat sink stream. and T_{source} is the target temperature of the heat source stream in °C or K. A higher T_{lift} which is the difference between target temperatures in the evaporator and condenser, results in lower COP and increased electricity consumption in the compressor. Conventional Electricity is at 0.036 \$/kW.h while renewable electricity price is 0.0102 \$/kW.h (IRENA, 2023). Fuel for conventional utilities is Natural Gas (NG), priced at 0.1 \$/m^3 (EIA, 2024).

Table 1: Steam properties and specifications

Mains	Specific Enthalpy (kJ/kg)	Temperature (°C)	Pressure (barg)
High Pressure (HP)	2801.0	250	41
Medium Pressure (MP)	2798.2	212	30
Low Pressure (LP)	2725.5	134	3

CO_2 taxes were imposed on the emissions generated in the case study for all different scenarios, with a CO_2 emission factor of 1.94 kgCO_2/m^3 and a tax of 35.3 \$/t of CO_2 (EPA, 2022).

Equipment cost estimation followed guidelines by Smith (2016). Cost data is represented through charts showing costs relative to equipment capacity or expressed as a power law of capacity:

$$C_E = C_B\left(\frac{Q}{Q_B}\right)^M \tag{2}$$

Where C_E is the equipment cost at Q capacity, C_B is the base cost for equipment of Q_B capacity, and M is an equipment type dependent constant.

Capital costs of electric boilers are estimated using CAPEX factors from the literature. For boilers over 10 MW, the CAPEX factor is 0.12 MM\$/MW (Zuberi et al., 2021). For smaller capacities, investment costs are calculated based on a correlation between boiler size and investment cost (Zuberi et al., 2022).

$$Capital\ Cost = Capacity\ (MW) \times CAPEX\ factor\ (\$/MW) \tag{3}$$

Table 2: Equipment capital cost correlations

Equipment	Q_B	C_B	M	Construction Material
Compressor	250 (kW)	9.84	0.46	Carbon Steel (CS)
Steam Boiler	50,000 (kg/h)	4.64	0.96	CS

2.3 Electrification framework

The electrification of heating utilities is delivered through a heat pump if the pinch temperature permits the placement of HTHP across the pinch. Applying it depends on the target temperature of the plant process streams and allowable T_{lift} for a reasonable COP which should always be higher than one. When the HTHP cannot utilize low-grade heat and a heat pump is not applicable, then an electrode boiler should be considered to deliver steam for target temperatures less than 350 °C which is the maximum temperature an electrode boiler could provide steam at, as superheated steam (Hechelmann et al., 2020). For plants where temperature ranges are higher than 350 °C, an electric furnace is suggested. Figure 1 provides step-by-step guidelines as an algorithm for easier navigation.

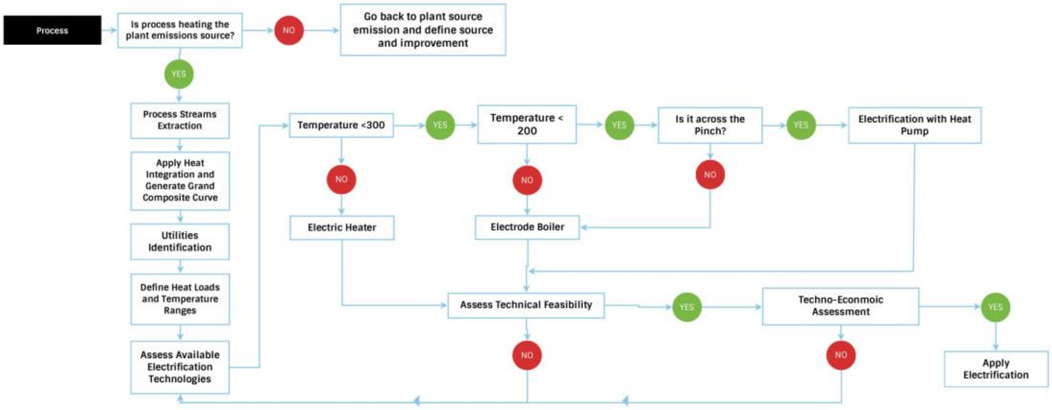

Figure 1: Electrification implementation and assessment guidelines

3. Results and discussion

The natural gas processing plant was chosen as a case study to assess the electrification of an energy-intensive industrial plant using a previously provided framework and guidelines.

3.1 Case study

The NG plant was simulated, and process stream data was extracted to apply heat integration. Medium Pressure (MP) steam was sufficient for the temperature interval of the required heating utilities. Heat integration covered most of the heating utilities required for temperature targets over 215 °C.

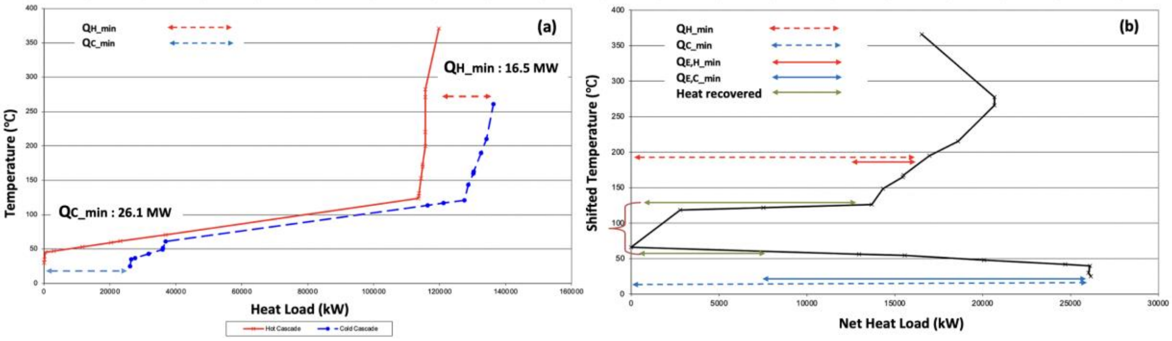

Figure 2: Pinch Technology curves for NG processing plant, (a) Composite Curve (b) Grand Composite Curve

The minimum heating utility for the plant after heat integration, Q_{H_min}, is 16.5 MW, and the minimum cooling utility, QC_{min}, is 26.1 MW, as illustrated by the CC shown in Figure 2(a). Further reduction of minimum utilities was possible using electrification as demonstrated by the GCC presented In Figure 2(b), where the side bracket indicates the placement of the heat pump utilized. The solid lines on the GCC represent the heat recovered by the heat pump, and the minimum utilities after utilizing waste heat from below the pinch are shown as Q_{E,H_min} for heating, and Q_{E,C_min} for cooling. Multiple scenarios of the case study were generated to compare electricity prices and the effect of it on operating costs and compare the capital cost of electrification with conventional technologies.

Case study Conventional utilities, off-site and on-site production

Conventional MP steam serves as the heating utility and is sourced externally from another power plant for off-site production. This incurs no capital costs, but the operating costs are determined by the steam purchase price, including CO_2 taxes in the TAC. On-site steam production involves estimating the capital cost of a steam boiler using the power law of capacity. The primary aim of incorporating on-site production to this scenario is to compare capital costs of conventional technologies with those of electrified alternatives.

Partial electrification with renewable electricity

As the heat pump was applied, it reduced the QH_min by over 83 %, and because of the utilization of hot streams below the pinch, the QC_min was also reduced by 26 %; however, the cost savings of cooling utilities were not calculated or accounted for in the cost analysis in this study. This scenario applies only to HTHP as an electrification technology, and the remaining heating utilities were covered by conventional MP steam. The industrial heat was partially electrified, which resulted in lower annualized costs and an 80 % reduction of emissions.

Full electrification with renewable electricity

Both HTHP and electrode boiler were employed to fulfill the heating utility requirements, this eliminates all of CO_2 emissions. Nonetheless, as anticipated, this scenario had the highest operating cost due to renewable electricity price. A comparison of costs across various scenarios, as illustrated in Table 3, indicates that electrifying all industrial heat may not be the most economically favorable strategy.

Table 3: Costs and emissions results of all scenarios

Scenario	Energy consumption (MW)	Capital cost (MM$/y)	Operating cost (MM$/y)	CO_2 tax (MM$/y)	CO_2 emissions (kt/y)	CO_2 reduction (%)	TAC (MM$/y)
Conventional							
- Off-site	17.64	-	1.79	1.04	29.5	-	2.83
- On-site	17.64	0.46	1.4	1.04	29.5	-	2.44
Partial electrification (RE)	12.0	0.8	5.9	0.17	4.9	83	7.9
100 % electrified (RE)	11.8	1.2	7.8	-	0	100	6.1
100 % electrified (Conventional)	20.6	1.2	4.0	1.2	34.5	-	5.3

Electrification with conventional electricity

In this scenario, the same electrified technologies were applied as the full electrification utilizing renewable electricity, resulting in the complete electrification of industrial heat. The aim was to assess the reduction in operating costs at conventional electricity price, which reduced the cost from 7.8 MM$/y to 4.0 MM$/y. While this scenario almost halved the operating costs, it also led to increased energy consumption, stemming from less efficient conversion between energy forms and the inevitable heat losses. Similarly, emissions from the plant rose due to the combustion of fossil fuels for electricity generation and higher energy consumption.

3.2 Mini-MAC

The Minimum Marginal Abatement Cost curves (Mini-MAC) are generated through an algebraic targeting technique (Lameh et al., 2022). These curves provide a visual representation of available CO_2 emissions reduction options, illustrating how they stack up against each other in terms of cost per ton of CO_2. Unlike the original methodology, where pathways/strategies are cumulative and can be simultaneously implemented for optimal decarbonization, this is not the case in this study. The pathways presented on the curve are not cumulative but rather intended to be selected on a case-by-case basis. The Mini-MAC is chosen for its clarity, enabling planners to easily select the most cost-effective pathways for reducing CO_2 emissions.

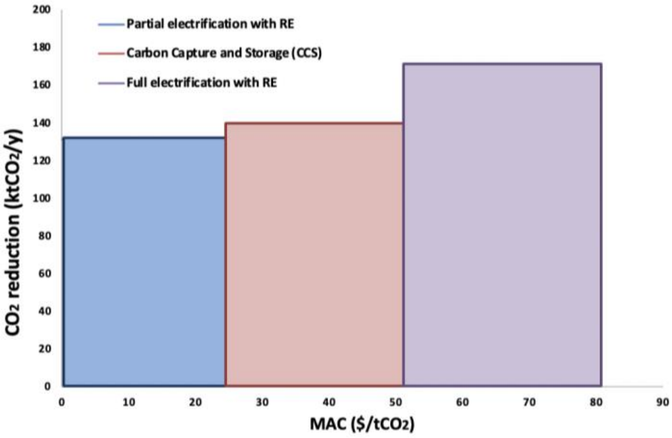

Figure 3: Mini-MAC of decarbonization pathways

Figure 3 displays the three feasible decarbonization strategies outlined in this case study. Following the implementation and evaluation of electrification using the proposed framework, one of the assessment tools utilized is the Mini-MAC curves. In addition to the two electrification scenarios—partial and full—a Carbon Capture and Storage (CCS) investigation was conducted for the natural gas processing plant. While CCS is a well-established technology, it remains costly and lacks studies on the effects and environmental impact of carbon sequestration in the long run. Results indicate that partial electrification yielded the lowest abatement cost at 131 $\$/\text{tCO}_2$, compared to CCS at 140 $\$/\text{tCO}_2$. Electrification using conventional electricity was not represented as it resulted in higher emissions than the base case of conventional utilities.

3.3 Challenges and opportunities

The pathway to decarbonization, aimed at achieving a net-zero energy system by 2050, presents both opportunities and challenges. The development of a systematic approach and a guiding framework to evaluate electrification as a decarbonization strategy for the chemical industry is one of the critical steps towards achieving environmentally conscious industrial processes in alignment with global climate goals. This study provides a structured unified approach to identify suitable electrified technologies to optimize energy consumption and evaluate the economic and environmental impact of electrification, which proves to be a practical pathway towards carbon emission reduction in industrial processes.

While scaling electrification to include energy-intensive industries emerges as a promising pathway towards achieving global climate goals, multiple challenges need to be addressed. These challenges include technological barriers, economic considerations, and policy frameworks. Realization of electrification feasibility the pressing need to address practicality in terms of infrastructure, grid integration, and resource availability.

Opportunities for innovation arise through the adoption and refinement of the proposed structured approach, which will enable stakeholders to have a more efficient process of implementing electrification and identify cost-effective solutions for decarbonization. Development in the areas of electrified technologies, grid integration strategies, and policy frameworks would also aid in accelerating progress towards decarbonization goals.

4. Conclusion

Overall, the development of a structured framework contributes to the creation of comprehensive and unified decarbonization strategies for the chemical industry. Applying this study's systematic approach to a natural gas processing plant demonstrates that electrification can be economically competitive with well-established decarbonization technologies, such as CCS, with a 6 % lower cost per ton of CO_2 reduced when the optimal ratio of electrified to conventional technologies is reached. The electrification scenarios resulted in over 80 % reduction in emissions. Considering these findings, the systematic methodology presented offers a promising decarbonization pathway toward a greener future.

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