ELECTRIFICATION OF REFINING PROCESS HEAT AS A PATHWAY TO DECARBONIZATION

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Damien FERAL
Schneider Electric
Lyon
France

Marco ARTUSI
Schneider Electric
Milan
Italy

Thomas Alan KWAN
Schneider Electric
Boston, MA
United States

Abstract - The process industries, particularly petroleum refining, face mounting pressure to reduce greenhouse gas emissions while maintaining operational viability, with refineries accounting for approximately 4% of global CO_2 emissions from stationary sources. As the energy transition accelerates, electrification emerges as a key decarbonization strategy, enabled by the growing availability of low-carbon electricity and advancing electric heating technologies. However, implementation requires careful evaluation of technical feasibility, economic implications, and operational impacts.

This paper examines the multifaceted challenges of industrial electrification through a detailed case study of a Western European refinery targeting 23% emissions reduction by 2030, analyzing the implementation of electric heating systems across multiple process units and associated infrastructure requirements. The study evaluates various electrification technologies, electrical system configurations, and operational considerations while quantifying both capital and operational expenditures through detailed technical and economic analysis.

The case study demonstrates that achieving 20% refinery electrification (twice the EU refineries average) is technically feasible and can deliver significant emissions reductions, while reducing total energy consumption by 5.1% through improved energy efficiency. Economic analysis reveals that while operational costs increased by 51% under the modeled electricity pricing (€200/MWh), strategic voltage selection and infrastructure optimization delivered 24% capital cost savings, with breakeven scenarios identified through sensitivity analysis of electricity costs and carbon pricing mechanisms.

I. INTRODUCTION

The global imperative to address climate change has placed unprecedented pressure on industrial sectors to dramatically reduce greenhouse gas emissions while maintaining operational and economic viability. Within this context, the petroleum refining industry, accounting for approximately 4% of global CO_2 emissions from stationary sources [1], faces scrutiny due to its energy-intensive processes and historical reliance on fossil fuel combustion. Process heating, which represents the largest share of direct emissions in refineries, has emerged as a critical target for decarbonization efforts [2].

The evolution of industrial processes over the past century has been intrinsically linked to the availability and economics of fossil fuels, resulting in deeply embedded technological dependencies that present significant challenges for transformation [3]. However, the accelerating energy transition, characterized by rapidly expanding renewable electricity generation and declining costs of electric technologies, has created new opportunities for industrial decarbonization through electrification. This shift is further catalyzed by increasingly stringent environmental regulations and corporate commitments to emissions reduction targets [4].

Electrification of process heating represents a fundamental transformation in how refineries operate, requiring careful consideration of technical feasibility, economic implications, and operational impacts. The integration of electric heating technologies into existing refineries must address multiple interconnected challenges, from the modernization of electrical infrastructure to the maintenance of process reliability and optimization of energy balances. These considerations become particularly critical when pursuing ambitious emissions reduction targets within compressed timeframes, as demonstrated by the case study in this paper.

Recent technological advances have expanded the potential applications of electric heating in industrial processes, offering improved control precision and energy efficiency compared to conventional combustion-based systems [5]. However, the practical implementation of these technologies at scale requires a detailed understanding of their capabilities, limitations, and integration requirements. Furthermore, the economic viability of electrification initiatives depends heavily on regional electricity costs and carbon pricing, policy mechanisms, and the ability to capture additional operational benefits beyond emissions reduction.

This paper examines these multifaceted challenges through a comprehensive analysis of electrification initiatives at a Western European refinery. The case study provides insights into the technical, economic, and strategic considerations that influence the success of industrial electrification projects. By analyzing actual implementation experiences and outcomes, this study contributes to the growing body of knowledge supporting industrial decarbonization efforts while highlighting critical factors for consideration by facilities pursuing similar initiatives. The findings presented here are particularly relevant given the increasing pressure on industrial facilities to develop and execute credible decarbonization strategies. As the energy transition accelerates and policy mechanisms mature, understanding the practical implications of process electrification becomes essential for strategic planning and investment decisions. This study addresses this need by providing a detailed analysis of implementation challenges, economic trade-offs, and strategic approaches to successful electrification projects.

II. ACHIEVING DECARBONIZATION WITH ELECTRIFICATION

The transition toward electrified process heating in industrial applications represents a complex technological and operational transformation that demands careful consideration of multiple interconnected factors. For example, oil refining's Scope 1 and 2 emissions come from multiple sources mostly linked with process combustion, utilities generation, and production of hydrogen (Fig. 1). This section examines the fundamental approaches, technical considerations, and implementation strategies that enable successful electrification initiatives while maintaining operational reliability and economic viability.

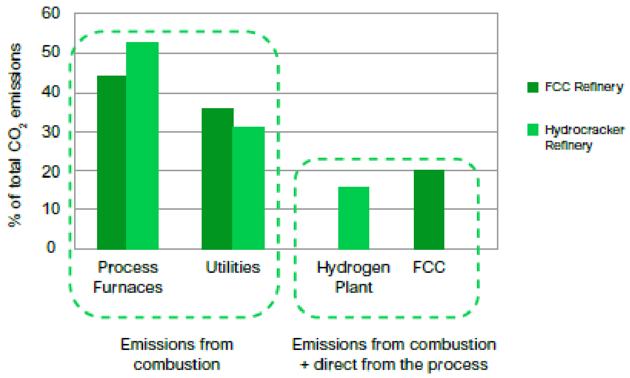

Fig. 1 Typical oil refinery CO_2 emissions sources [6]

A. Technological Framework and Infrastructure Requirements

Industrial process heating applications encompass a wide range of temperature requirements and heating profiles, necessitating diverse technological solutions. Various electric heating technologies are available for industrial applications, which can produce temperatures above 1000°C, though their specific applications and performance characteristics must be carefully evaluated for each process requirement [7-9]. The integration of electric steam generation systems and heat pumps further expands the potential for thermal integration and energy recovery. Studies have shown that industrial heat pump systems can achieve coefficient of performance (COP) values of 4.2, with solar-assisted systems reaching up to 5.2 [10].

Successful electrification initiatives require a comprehensive evaluation of existing infrastructure capabilities and necessary upgrades. The analysis must consider not only the immediate power requirements of electrified processes but also the broader implications for electrical distribution systems, control infrastructure, and backup power provisions.

The integration of electric heating systems should also account for process and operational flexibility requirements, while modern electric heating systems can achieve more precise and faster temperature control compared with conventional combustion-based systems. In addition, space constraints and integration with existing equipment require innovative engineering solutions regarding footprint and implementation.

C. Economic Considerations and Strategic Implementation

The economic viability of electrification projects depends heavily on regional electricity costs, policy, potential carbon pricing mechanisms, and operational benefits. Both oil refineries and petrochemical plants self-generate the fuel needed to operate. This fuel is complemented by imported energy to satisfy the process demand (Fig. 2). At the studied refinery, electricity costs (200 €/MWh) were approximately 4.2 times higher than natural gas costs (48 €/MWh), highlighting the significant operation cost differential that must be considered when evaluating electrification initiatives. However, this differential must be evaluated against improving efficiency, reduced maintenance requirements, evolving policy and applicable carbon pricing schemes.

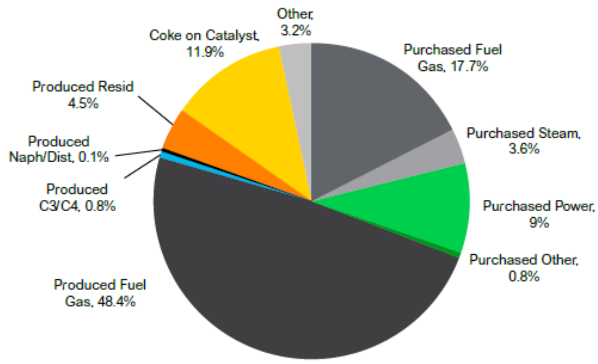

Fig. 2 EU-28 Refineries average energy mix (2016) [6]

This case study demonstrates the importance of strategic implementation planning through a phased approach aligned with technical and business priorities. Integration with broader efficiency initiatives delivered measurable benefits. In this study, a 5.1% reduction in total energy consumption was achieved through higher efficiency of electrical heaters and a motor. Comprehensive energy balance analysis becomes critical, particularly in facilities such as oil refineries and petrochemical plants with integrated heat recovery systems and complex steam networks.

D. Risk Management and Future Considerations

The implementation of electrification initiatives must address risk factors through careful planning and mitigation strategies. Power supply reliability is increasingly important as electrical dependency grows, which in turn requires robust backup systems and contingency planning. The potential for demand response programs and energy storage integration offers opportunities to optimize operating costs while providing grid support services, though these capabilities must be evaluated against specific process stability requirements and scheduling.

Future developments in electric heating technologies and declining renewable electricity costs are expected to further improve the attractiveness of electrification initiatives. Additionally, the potential for hydrogen integration and hybrid heating systems offers flexibility in managing energy costs while maintaining progress toward decarbonization goals [11]. This comprehensive approach to electrification, considering technical, economic, and strategic factors, provides a framework for the successful implementation of industrial decarbonization initiatives.

III. CASE STUDY – PROCESS HEAT ELECTRIFICATION OF A EUROPEAN REFINERY

A. Electrification's Drivers and Potential

A Western European oil refinery is part of an energy company manufacturing conventional fuels and sustainable energies committed to Net Zero targets achieved by 2040. It has already implemented or planned several carbon reduction projects, but more efforts are needed to achieve an ambitious target of 23% emissions reduction by 2030 compared with the 2019 baseline. Electrification is considered a pathway to reach the target.

In addition to decarbonization, improving the reliability and operating efficiency by switching to electrically powered processes is also considered a key driver for the refinery. Hence, the set of equipment to electrify does not include only high CO_2 emitters but also small fired heaters which were planned for retrofitting.

The refinery's energy mix (Fig 3) consists of 46% coming from the refinery fuel gas generated by the process. Butane, one of the refinery's product, is being used as fuel, accounting for 26% of the energy mix, while imported natural gas contributes to 20% of the total (excluding natural gas imported as feedstock to produce Hydrogen necessary for the refinery). Electricity is imported from the grid and represents 8% of the mix. The majority (81%) of the energy is then used for process heating in fired heaters, while 11% is used to generate steam (which is used both for process heating and to power steam-driven compressors). The electrification of process equipment will lower the demand for fuel gas and, hence, displace natural gas imports and injected Butane into the mix.

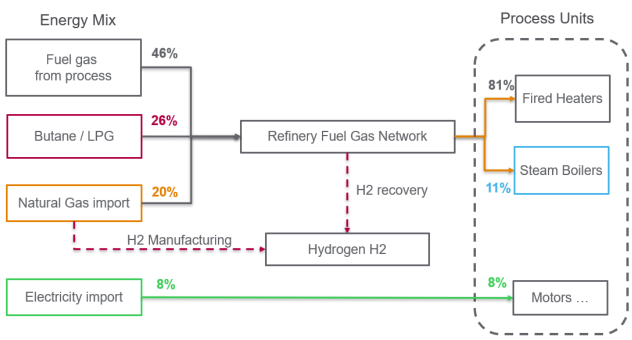

Fig. 3 Refinery's actual energy mix – yearly average

To avoid an unbalanced situation where the generated fuel gas from the process becomes excessive (which could lower the refinery's throughput or flare the excess gas when no export capacity is available), the electrification strategy must consider this fuel balance aspect. Additionally, the heat demand being significantly lower during the summer period (higher external temperature allowing for less overall thermal losses), a "worst-case scenario" where natural gas import is stopped, and only a fraction of Butane is injected into the fuel network is limiting further the electrification potential.

Similarly to the energy mix and fuel gas balance, steam that is produced and used onsite will be affected by the electrification of some equipment. Specifically for the refinery (Fig 4), steam is generated by several gas-fired boilers and from waste heat recovery (from various process heaters and a hydrogen manufacturing unit). It is then distributed and consumed by process equipment (general heaters, distillation reboilers, vacuum ejectors, turbines …) at different pressure and temperature levels. A balancing valve allows the downgrade of high or medium pressure to lower pressure to balance between generation and demand, when necessary, while a venting valve allows for evacuating any excess of low-pressure steam that may occur.

Those two elements represent an inefficiency in the system (as they waste energy) and are normally closed in operations. When electrifying steam consuming equipment, the existing balance between generation and demand is modified, and a new optimal generation and distribution strategy must be investigated.

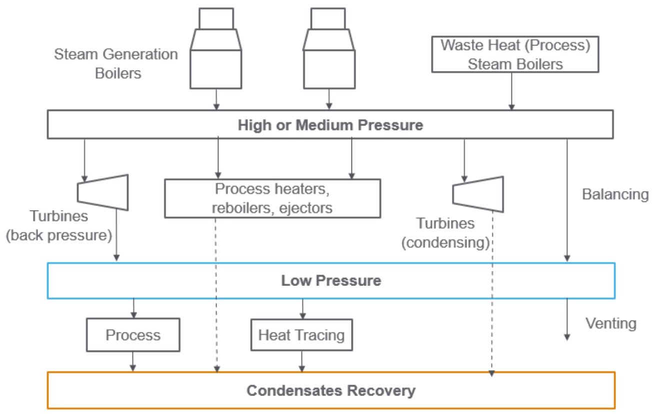

Fig. 4 Refinery's steam network configuration

B. Electrical System Configuration

The refinery has been operational for several decades, during which its electrical system has undergone numerous upgrades and modifications. All the power required to support the refinery's electrical system (Fig 5) is sourced from a redundant high-voltage connection to the external utility grid and supported by an internal 10MW PV system. Within the refinery, the power distribution system adopts a fault-tolerant double radial configuration with 100% redundancy up to the main low-voltage bus, ensuring a high level of availability.

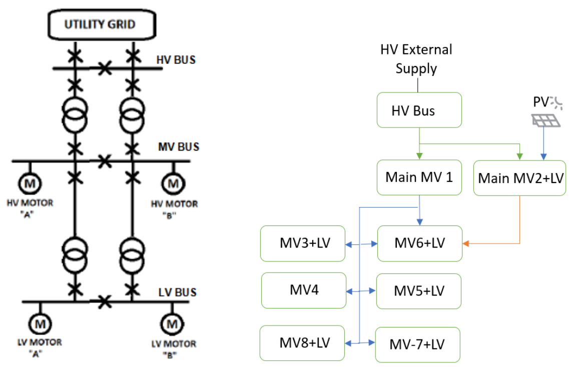

Fig. 5 Refinery's existing electrical distribution philosophy

The electrical power distribution system includes two main substations to step-down high voltage supply and multiple secondary substations to distribute medium voltage and feed low voltage process loads.

From the electrical point of view, the main streams assessed for feasibility are:

- ✓ The provision of additional power to the plant's load.
- ✓ The required electrical infrastructure upgrade of the plant.
- ✓ The electric distribution and supply to the electrified loads.

C. Electrification Opportunities and Technologies

Considering the above aspect related to the CO_2 emissions, energy mix and balances, a screening of the refinery's process equipment allows to identify potential targets for electrification (Fig. 6). Several other criteria were considered, related to the size of the equipment (process heat or shaft duty), the actual energy efficiency of the equipment, the side impacts of electrification (such as loss of heat recovery from fired heater flue gas or steam condensates), reliability or operability issues (equipment requiring frequent maintenance or troubleshooting, already planned for upgrade, and more).

The results of the process screening together with the planned plant upgrades identify a list of candidates that would contribute to the reduction of refinery's CO_2 emissions, complemented by other planned modifications affecting the electrical distribution. More specifically:

- ✓ Electrification of 9 process heaters with duties in the range of 100 kW to 10 MW, including gas-fired heaters, steam-based heaters, distillation steam reboilers used in various process units treating naphtha, gasoline, kerosene or acid gas.
- ✓ Electrification of <5 MW a steam turbine-driven recycle gas compressor used in a catalytic process unit.
- ✓ Addition of a new electric driven compressor planned to debottleneck the H_2 recovery unit from the refinery's fuel gas system.
- ✓ Expansion of the refinery's photovoltaic (PV) solar system for the whole car parking area.
- ✓ Addition of planned electric vehicle (EV) charging station for heavy trucks and cars

Eventually, the total electrical load demand of the refinery is expected to increase by >100% compared with the actual situation. To select the best-fitting solutions, a techno-economic assessment has been performed to identify and evaluate relevant electrical technologies against process and energy requirements as well as CO_2, electrical and other technical and financial impacts (efficiency, energy balance impact, installation complexity, costs, etc).

Table 1 below shows an extract of various assessed electrical heating technologies applicable for Refining and Petrochemicals process heating, with some key outcomes related to technical capabilities and targeted applications.

TABLE I

Electrical Heating Technologies Assessment - Extract

	Process to Electrify - Criteria		
Electrification Technologies	**Gas-Fired Heater**	**Steam Reboiler**	**Gas-Fired Steam Boiler**
Resistive Heater	1-10 MW Clean fluid	Kettle type reboiler	-
Radiant Heater	>10 MW Heavy or fouling fluid	High heat flux reboiler	-
Electric Boilers ✓Resistive ✓Electrode	-	Decentralized steam heater or reboiler	Low to High pressure steam
Heat Pumps	Temperature limitation	Close boiling points distillation	Low pressure steam

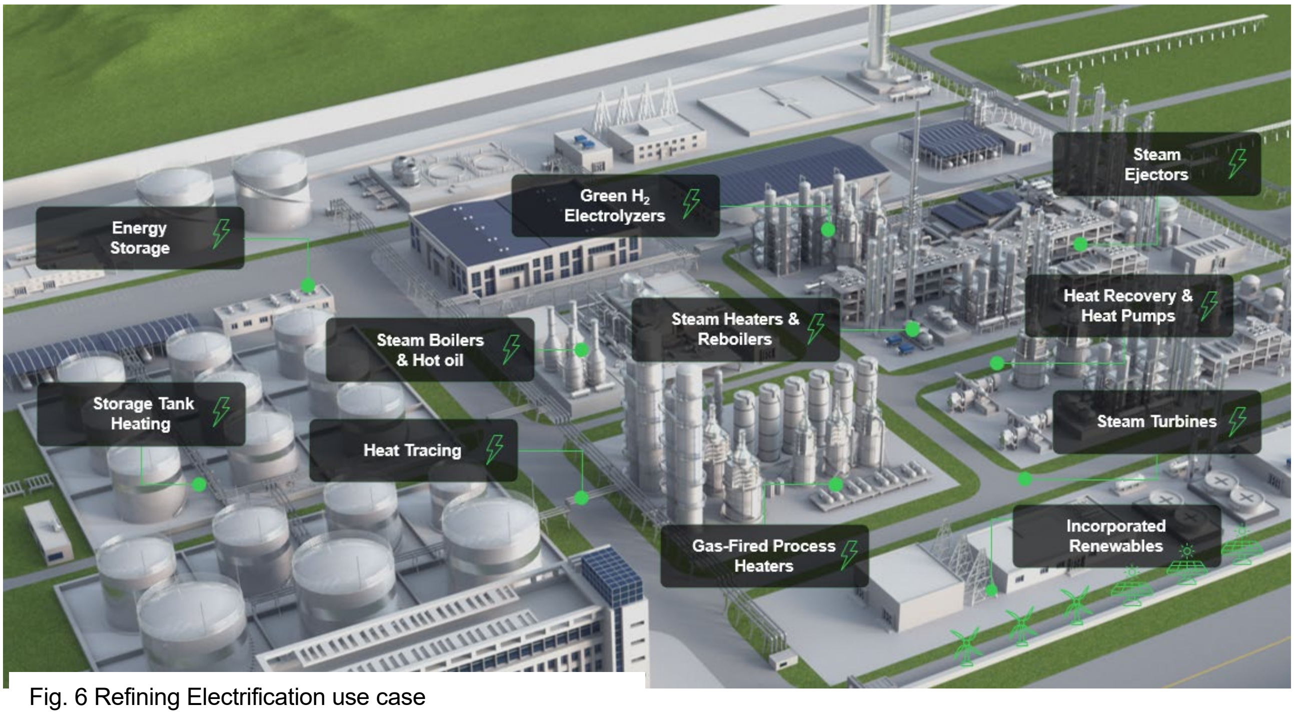

Fig. 6 Refining Electrification use case

D. Future Electrical Power Balance and Energy Sourcing

The refinery's current electrical power demand remains relatively stable throughout the year, exhibiting minimal seasonal fluctuations. Any additional loads from process electrification should be considered at full capacity, without applying any contingency factors. An exception to this is the electric vehicle (EV) charging stations, which constitute only a minor fraction of the overall load.

The two high-voltage (HV) underground cable connections between the refinery and the utility grid currently operate at 30% capacity, ensuring supply redundancy (or N+1 configuration). A projected 100% increase in power demand will push each line's load over 50% of capacity, compromising this redundancy. Upgrading the HV cables could preserve the N+1 configuration but poses challenges:

Underground cable upgrades are more expensive than overhead lines due to the need for horizontal drilling.

The utility grid operator cannot upgrade the cables for at least five years, possibly up to ten years, which conflicts with the 2030 CO_2 reduction deadline.

As an alternative to ensure the full resilience of the refinery's power system, the connection of a combined cycle power generation facility is considered. This facility would be optimally sized to meet the increased power demand and potentially provide ancillary services to the grid. However, this solution is capital expenditure (CapEx) intensive and, to avoid negative impacts from a CO2 reduction perspective, would require the use of clean fuels such as biogas or green hydrogen, which would further increase operational expenditures (OpEx).

Finally, the recommended option is to maintain the existing cable connections with the grid and enhance the plant's electrical control system so that, in the event of a failure, the electric heater power will rapidly ramp down.

Such a solution minimizes CapEx and OpEx and is supported by the high reliability index (SAIDI and SAIFI) of the external utility grid as well as additional considerations, such as:

- ✓ The future plant electrical load will not be constant as it was before since the total power demand will now be affected by the thermal demand of the process, which will be subject to seasonal variation.
- ✓ The worst-case scenario considers a single HV cable connection loaded at 120% of capacity; therefore, the reduction of 20% load on the electrified heaters will not cause the shutdown of the process but only limit operations below rated capacity.

Regardless of the selected option, it is imperative for the end user to proceed with the application process to upgrade the HV connection with the utility grid, as the 2050 target for CO_2 emissions may necessitate further expansion of process electrification. In this scenario, the existing connections may become a significant bottleneck.

E. Electrical Infrastructure Upgrade

The drastic increase in plant electrical power demand exceeds by far the spare capacity of existing main step-down transformers connected to the HV bus. In addition, the available space in the existing electrical substation is not suitable to accommodate new MV switchgears and large power converters associated with new electrical heaters and compressors. Similarly, the existing indoor HV switch room is not rated for the new power demand and needs to be upgraded or replaced by a new one.

From a plant layout perspective, the new electrical loads are spread across the whole refinery (Fig 7) with distances from the closer electrical substation that range from 70m up to 350m.

HV system upgrade

The options to accommodate the extra capacity on the HV system are mainly to upgrade the existing HV air-insulated bus or to install a new HV switchgear, and the decision is influenced by multiple factors such as:

- ✓ Impact on process operations
- ✓ Cost
- ✓ Space availability
- ✓ Impact on utility grid connections

The new HV switchgear option offers the advantage of minimizing risks during the construction phase, as the new substation can be installed without disrupting the existing system operation. However, space constraints necessitate relocating the substation 350 meters from its current location, and the available plot size would require the consideration of GIS technology.

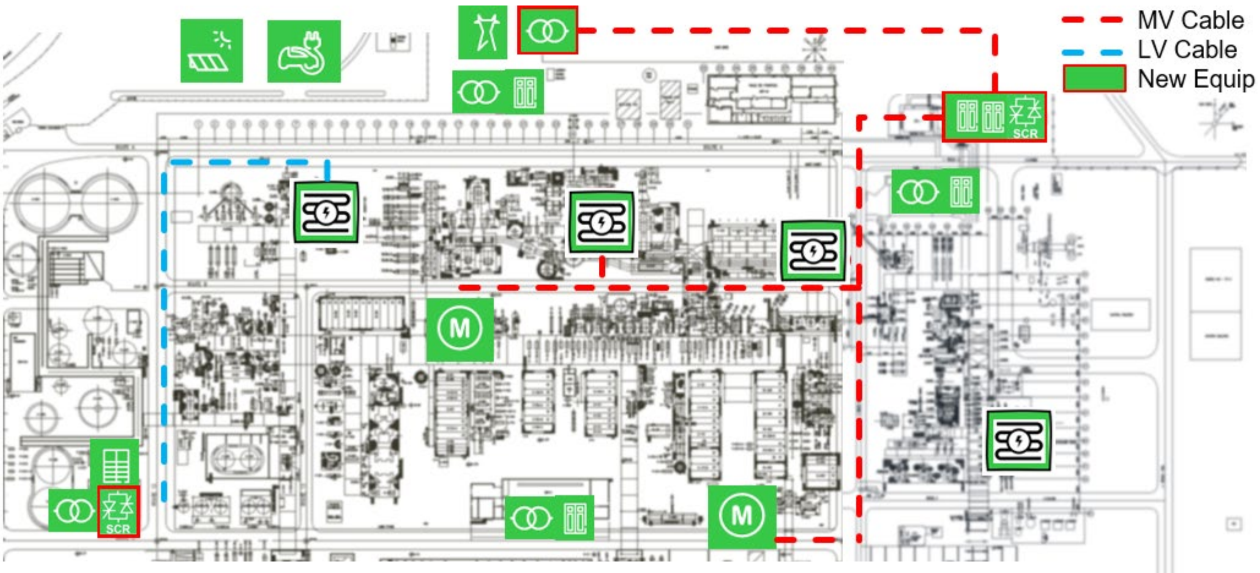

Fig. 7 Electrical infrastructure upgrade layout

This technology, while more costly, would also increase the plant's greenhouse gas (GHG) inventory. Additionally, replacing the existing HV bus would require extending the current HV cables owned by the utility grid within the plant area perimeter, which could introduce further complications. Furthermore, the future extension of process electrification to meet the CO_2 reduction target for 2050 could potentially increase power consumption by 200%. Consequently, the new total power demand might necessitate connecting the plant to a higher power distribution level of the utility grid, such as 220kV.

Based on the above considerations, the recommended solution is to upgrade the existing HV switch room since the available plot space can accommodate the new feeders for two additional step-down transformers and even a feeder to the cogeneration plant. In addition, the existing HV cable connections will not be impacted, and with proper risk management, the upgrade of the HV bus can be performed without affecting plant operation.

Voltage rating optimization for new loads

The selection of the appropriate voltage level for new electrical equipment is essential for optimizing capital expenditures (CapEx) and ensuring efficient operation. This decision results from multiple factors, including:

- ✓ Cost of the heating element and control panel
- ✓ Spare capacity on existing switchgear
- ✓ Cost of associated electrical infrastructure
- ✓ Constraints of existing installations

It is often necessary to compare multiple options to identify the most suitable one in terms of equipment and installation cost. New electric motors for compressors with power rating >1MW are considered to be fed directly from MV bus as per the refinery's design practice, while the new EV charging station and PV system of the car parking area are considered to be supplied at LV through dedicated 3MVA transformer fed by a spare feeder of the existing switchgear.

The primary factor influencing the upgrade of the electrical system architecture is the selection of the voltage rating for new process electric heaters. Resistive electric heaters can be designed considering either LV or MV supply up to 6.6kV (while some specific radiant heaters can be supplied only at LV level). Depending on the power rating, it would be necessary to split the heater supply into multiple electrical sub-circuits that range from 300kW up to 2.5MW. Considering only the cost of heating elements and associated thyristors control panel, the LV heater option will cost approximately 40% less than the MV solution (hybrid architecture consisting of thyristor and contactors is possible but requires detailed thermal analysis) and it will also benefit from a higher efficiency (by 3 to 5%) related to a lower insulation thickness of the heating element. The decision between these options hinges on a detailed analysis of the specific requirements and constraints of the plant, considering both initial costs and long-term operational efficiency.

Four (4) smaller process heaters subject to electrification belong to the same process unit and their overall combined power will not exceed 500kW. Power flow verification confirms that within the existing electrical substation associated with the specific process spares, the spare capacity of LV MCCs and relevant power distribution transformers can accommodate the new loads. The proposed voltage rating in this case would be 400V since such a solution is optimized in terms of equipment cost and it would not introduce any additional cost to upgrade the electrical infrastructure.

For large heaters exceeding 2MW in capacity, the feasibility of supplying them at either low voltage (690V) or medium voltage (6kV) has been assessed. When considering the supply of the heater at low voltage, the preferred solution is to install step-down transformers and thyristor panels close to the heaters to reduce cables and installation costs. However, several challenges have been identified:

- ✓ Electric heaters are located in hazardous areas (ATEX classification). Special design considerations are required to install power transformers and switchgears.
- ✓ All structures within the process area must be blast-resistant, and the refinery has declined the use of prefabricated E-houses, which would reduce the construction activities. So, there would be necessary concrete stitch-built substations that require extended time for construction.
- ✓ The addition of E-houses within the process area may affect the maintainability of the existing installation, as they could interfere with zones designated for heavy lifting cranes.
- ✓ In certain instances, the available space near the heater encroaches upon existing emergency evacuation routes.

All the above points lead to the conclusion that independently from the voltage rating of the heaters, the new electrical equipment and distribution system should be located in a single electrical substation conveniently located at the border of the process area. The resulting proposed solutions for the heaters supply at either 690V or 6kV are outlined below (Fig. 8).

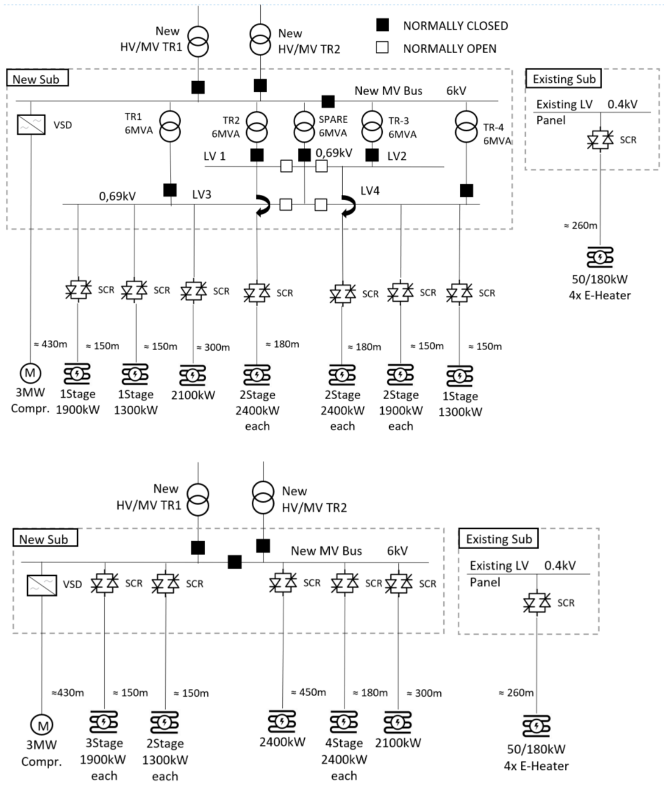

Fig. 8 Electric heaters power supply options

The comparison of the total cost of the two options indicates that the MV option is more optimized in terms of substation footprint, cable quantity and installation works.

In terms of OpEx the solution with LV heaters is also penalized by higher losses associated with additional power transformers and higher currents flowing into the cables. Therefore, the recommended solution is to supply the large heater at 6kV, as it would also be the optimized solution from CapEx perspective, as detailed in the next section.

F. *Study's Outcomes and Electrification Roadmap*

The refinery's Electrification of the 9 heaters and steam turbine will mostly impact the energy mix (fuel and steam balance) as well as the electrical system.

By doubling its electrical load to replace fuel-fired heaters and electrify some steam users, the refinery's energy mix will become 20% electrified (with a low-carbon electricity source) which is more than twice the European Union average of 9%. The imported Natural gas used to complement the refinery's fuel gas will be stopped by 100%, in addition to the incorporation of produced Butane (stopped by 100%, too) which will be exported as a product instead. During summer, when the refinery's heat demand is lower, the fuel gas system may become in slight excess of self-generated gas, which will be counterbalanced by the refinery's already approved plan to debottleneck their H_2 recovery unit (by adding an electrical compressor), minimizing the quantity of H_2 loss in the fuel gas (and by extension further minimize CO_2 emissions from the Hydrogen Manufacturing Unit).

Gas-fired generated steam can be saved when electrifying the identified steam reboilers and heaters by up to 40%, which will allow permanently stopping one of the 3 steam boilers in operation. Especially when replacing the large and inefficient condensing steam turbine with an electric motor, a slight rebalancing of the steam network using the letdown valve from Medium to Low pressure will become necessary. No loss or venting of Low-pressure steam is forecasted with the future configuration.

Globally, the refinery will see its global energy needs (gas and electricity) lowered by 5.1% due to higher energy efficiency of electrical heaters (close to 100% energy efficiency versus an average energy efficiency of 85% considered for gas fired heaters and steam boilers) and electric motor (close to 95% versus 30% for the condensing steam turbine).

A progressive implementation of the refinery's electrification (Fig 9.) is planned to align with technical and business priorities to achieve the decarbonization target of -23% CO_2 emissions.

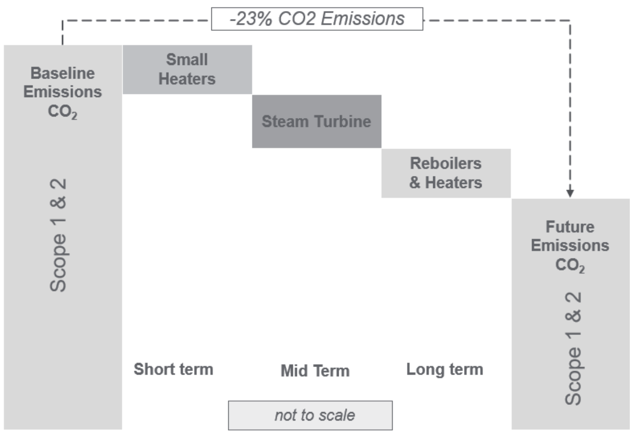

Fig. 9 Refinery's electrification roadmap

G. *Economic Analysis*

1) *Operational Expenditures*:

The main impact of electrifying the refinery's process on its OpEx (Fig 10) is a doubling of the low-carbon electricity cost being imported from the utility grid at an average price of 200 €/MWh. This effect is partially counterbalanced (by approximately a third) with gas import at a price of 48 €/MWh and steam production savings (including the gain in energy efficiency from electrified heaters). Additionally, a reduction in CO_2 emission will allow the refinery to save on the CO_2 quotas purchased at a price of 85 €/ton CO_2 in the European Union Emission Trading System. Nonetheless, despite those different savings, the OpEx business case remains negatively impacted by the high price of low-carbon electricity.

Overall, a +51% increase in the baseline electricity bill is expected by electrifying the process, considering current electricity, fuel gas, and CO_2 prices. To turn the scale towards a positive business case, it is crucial to identify other drivers by prioritizing aging process equipment with high maintenance costs, or that are known to cause operational upsets or trips, eventually cascading effects down to the refinery's margins. In such cases, stacking up those non-environmental benefits can lead to breakeven or even positive business cases.

Regarding the refinery, the steam boilers have been planned for replacement targeted by 2030 due to low reliability and high maintenance costs. Reducing the steam demand by electrifying the identified steam heaters, reboilers and a large steam turbine will allow the refinery to permanently stop one of the 3 steam boilers, saving on energy as well as maintenance costs. Up to 4 fired heaters were also planned for retrofitting in 2027 as their burners demonstrated poor reliability at the required low throughput operating conditions of their process unit. By replacing those with electrical heaters, the refinery will save on both the retrofit investment and the avoided unreliability cost. Finally, safety improvements from reducing combustion-based processes while upgrading to newer, more modern, and safer equipment can also bring short-term and long-term benefits by avoiding costly events or incidents.

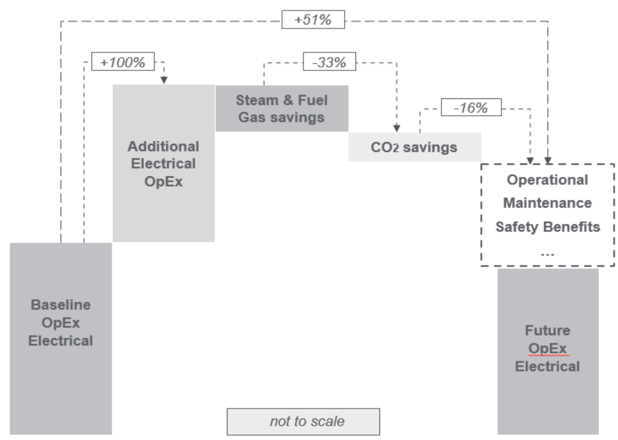

Fig. 10 Economics analysis – Operational Expenditures

A sensitivity analysis has been conducted in Table 2 by simulating prices for low carbon electricity and CO_2 tax. This results in the identification of several economic breakeven scenarios. In the electrification base case (scenario A), the actual prices of electricity and CO2 lead to an electrical OpEx increase of +51%. Scenario B illustrates a potential decrease in low-carbon electricity prices (by -35%). Nonetheless a significant increase in CO_2 tax price (+100%) remains necessary to reach a breakeven situation. Scenario C demonstrates the need to largely decrease the low carbon electricity price (-52%) without changes on the CO_2 tax to reach a breakeven situation. Scenario D shows the necessity of a significant increase in the CO_2 tax price (+250%) to absorb the extra electricity price.

TABLE II

Electrical Operational Expenditures - Sensitivity Analysis

Electrification Scenario	**Electrification Business Case**		
	Electricity €/MWh	CO_2 €/T	OpEx impact % of electrical
A – Base prices	200	100	+51%
B – Low electricity & High CO_2 prices	130 *Base -35%*	200 *Base +100%*	+0%
C – Low electricity price	95 *Base -52%*	100 *Base*	+0%
D - High CO_2 price	200 *Base*	350 *Base +250%*	+0%

2) *Capital Expenditures*:

Fig. 11 illustrates a comparison of the required CapEx for the two alternatives in terms of heater voltage ratings. The first option is to consider all new electric heaters to be powered by a new substation at 690V. The second option considers that only smaller heaters <1 MW powered at 400V leveraging spare capacity in existing Low Voltage switchgear and large heaters powered directly at Medium Voltage (MV) level of 6kV. Considering only the cost of new electric process heaters and associated control panels, the supply option at the LV level would be by far less expensive. However, considering all other aspects such as footprint, cost of electrical infrastructure upgrade, and losses in cables, the option to feed the large heaters at MV 6kV would be more attractive ensuring a CapEx saving of 24%.

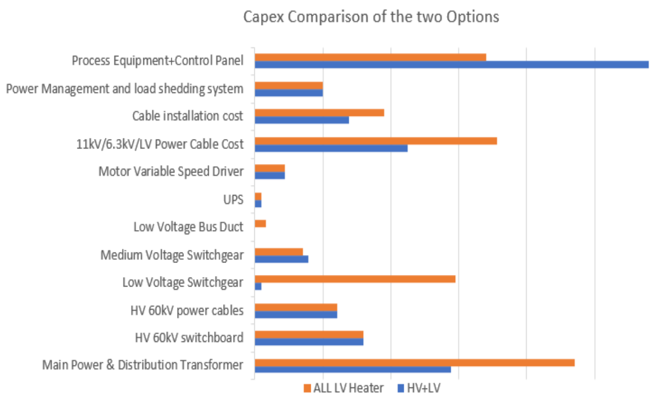

Fig. 11 Economics analysis – Capital Expenditures

IV. CONCLUSIONS

The comprehensive analysis of process heat electrification at a Western European refinery provides critical insights into the practical implementation of industrial decarbonization strategies. This case study demonstrates both the technical feasibility and complex challenges of large-scale electrification initiatives, while highlighting the importance of integrated planning and strategic implementation approaches.

The feasibility study validates several key theoretical frameworks discussed in the introduction regarding electrification as a decarbonization pathway. The refinery's successful implementation of electric heating across multiple process units, achieving a doubling of electrical load while maintaining operational stability, demonstrates the technical maturity of electrification technologies. The achieved increase in facility electrification to 20% of total energy consumption, more than twice the European Union average of 9%, establishes a benchmark for industrial transformation while highlighting the significant potential for further adoption.

Quantitative analysis of operational impacts reveals important insights for future implementations. The documented 5.1% reduction in total energy consumption, achieved through the superior efficiency of electric heating systems (approximately 100% versus 85% for conventional systems) and improved motor efficiency (95% versus 30% for steam turbines), demonstrates the potential for electrification to deliver both environmental and operational benefits. This improvement aligns with theoretical predictions while providing concrete evidence of achievable efficiency gains in real-world applications.

Economic analysis reveals both challenges and opportunities in electrification initiatives. The observed 51% increase in operational expenses under current electricity pricing (200 €/MWh) compared to conventional fuel costs (48 €/MWh) highlights the continuing challenge of cost competitiveness. However, the identification of breakeven scenarios through sensitivity analysis, particularly the potential for economic viability with a 35% reduction in electricity costs combined with carbon pricing of 200€/ton, provides valuable guidance for policy development and investment planning. However, with renewable energy costs continuing to fall, further consideration of how onsite renewables and/or power purchase agreements (PPAs) are warranted.

The study's findings regarding infrastructure optimization are particularly significant for future implementations. The demonstrated 24% capital cost reduction achieved through strategic voltage selection and infrastructure planning highlights the importance of systematic engineering analysis in project development. This outcome supports the theoretical framework presented in the second section while providing specific guidance for similar initiatives.

Furthermore, the research reveals important synergies between electrification and broader operational improvements. The ability to permanently decommission one of three steam boilers while improving process control precision demonstrates how electrification can catalyze broader operational enhancements. The successful integration with hydrogen recovery optimization further illustrates the potential for electrification to support comprehensive decarbonization strategies.

These findings have implications for future projects and analysis. The implementation approach provides a blueprint for systematic plant evaluation and execution of electrification initiatives. The detailed analysis of infrastructure requirements, technology selection criteria, and economic considerations offers valuable guidance for similar projects.

Looking forward, this case study identified several critical areas for future investigation. The demonstrated importance of electricity pricing and regulatory mechanisms in determining economic viability suggests the need for a detailed analysis of policy frameworks that could support industrial electrification. Additionally, the potential for demand response and energy storage integration to optimize operating costs warrants further exploration, particularly in the context of increasing renewable energy penetration.

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VI. VITA

Damien Feral is the Downstream Decarbonization Technology Director for the Energies & Chemicals segment at Schneider Electric. He graduated from the University of Chemical Engineering and Process (ENSIC) in Nancy, France, in 2010. He is a recognized industry expert with 15 years' experience with plants operators and Process Licensors in Oil Refining & Petrochemicals, driving process technical support, energy efficiency, decarbonization projects and commissioning of new process units globally.
In his current role, he advises the industry on the most efficient ways to decarbonize and optimize operations especially around the electrification of their processes and assets. He has authored several technical papers on industrial process electrification and sustainability.
damien.feral@se.com

Marco Artusi is a Senior Electrical Domain Expert for Schneider Electric within the Process Electrification Consulting group. He obtained a professional certification in Electrotechnics and Automation in 2006 and trained specifically in Renewable Energies at Politecnico di Milano in 2018. He has extensive experience in electrical engineering design, factory testing of electrical equipment, and field construction for large-scale oil, gas, and petrochemical projects. In his current role, he leads the execution of feasibility studies for energy-intensive industries aiming to significantly increase their electrical power consumption. He assists in optimizing the electrical system configuration at an early stage of the project to ensure integration with existing infrastructure, optimize project finances, and mitigate project execution risks.
Marco.artusi@se.com

Dr. Thomas Alan Kwan applies systems thinking and smart technology to develop advanced energy transition solutions that transform industrial systems and energy management. His research on process electrification and circularity has demonstrated significant carbon emissions and new business and operating models. He is Topic Editor for Green Chemistry and New Energy Systems for *Industrial & Engineering Chemistry Research* and writes the monthly 'Energy Savers' column in *Chemical Processing*. His work has yielded multiple patents in green chemical design, while his ability to translate complex concepts into practical business strategies has made him a valuable advisor for corporations transitioning to sustainable practices. Through innovative research and strategic leadership, he drives advancements in industrial decarbonization.
Thomas.kwan@se.com