



Electrification of the (petro)chemical industry

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EXECUTIVE SUMMARY

Industrial electrification is emerging as a central pillar for deep decarbonisation strategies for energy-intensive sectors such as (petro)chemicals, refining, steel, and cement production, Figure 1. In the (petro)chemical industry, direct combustion of fossil fuels for process heat and steam generation, as well as fossil feedstocks for synthesis, account for a large share of greenhouse-gas (GHG) emissions. Replacing these thermal and feedstock inputs with electricity from low-carbon sources and renewables can dramatically reduce emissions while enabling new process windows, improved controllability, and, in some cases, higher selectivity and product quality.^{1,2}

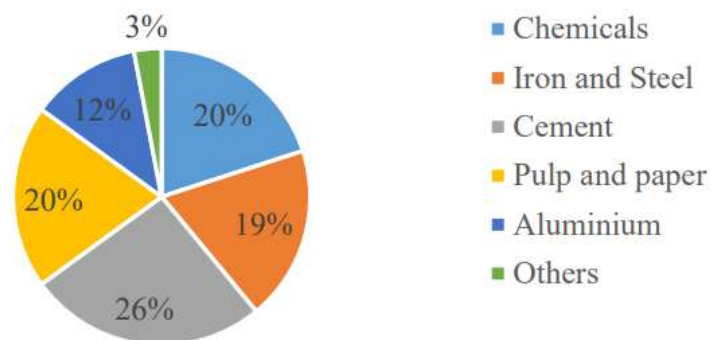


Figure 1: 2010 CO₂ emissions in energy intensive industries sectors.

This white paper synthesises insights from recent literature and e-CODUCT results on industrial electrification, with a particular focus on (petro)chemicals. It draws on techno-economic investigations of electrified ethylene production, analyses of European competitiveness and energy-system transition bottlenecks, and front-edge research on electrified catalytic reactors (including induction-heated systems).^{1,4-6}

Key messages are:

- Electrification of high-temperature unit operations (cracking, reforming, partial oxidation) is technically feasible and increasingly attractive as renewable electricity becomes more abundant and affordable.^{2,7}
- System-level constraints - in particular electricity-system flexibility, permit granting for renewables and grids, and investment risk - remain critical bottlenecks that must be addressed in parallel with technology development.^{1,4,7}
- In (petro)chemicals' production, electrification enables integration of CO₂ as a feedstock (e.g. for methanol or CO production), supports circular-economy strategies, and can be combined with advanced catalysis (induction, microwave, plasma) to unlock new reaction pathways.^{1,8,9}
- The e-CODUCT concept - an ElectroThermal Fluidised Bed (ETFB) reactor producing CO from waste CO₂ and H₂S using renewable electricity - is well aligned with these trends and can serve as a demonstrator for electrified, circular (petro)chemical value chains.^{1,2,7}

INTRODUCTION

The (petro)chemical industry underpins modern society by supplying building blocks for plastics, solvents, synthetic fibres, fertilisers, and a wide array of specialty chemicals. This comes at a climate cost: primary chemicals such as ammonia, methanol, ethylene, propylene, and aromatics are among the largest single sources of industrial CO₂ emissions. Traditionally, process heat is provided by natural-gas or fuel-oil burners firing large furnaces and boilers, while feedstocks are fossil-based (naphtha, ethane, methane, LPG).

Electrification offers an alternative paradigm. Instead of combusting fuel to supply heat, electrical energy - if supplied from low-carbon sources - can be converted into heat or directly into chemical work. Electrified unit operations include resistive (Joule) heating, induction heating, microwave heating, plasma-assisted reactions, and electrochemical processes (e.g. water electrolysis, electro-oxidation, or CO₂ electroreduction). These techniques can deliver high power densities and rapid temperature control, which are attractive for dynamic operation in an electricity system increasingly dominated by variable renewables.

At the same time, the energy-system context is changing rapidly. In Europe, high and volatile natural gas prices, combined with climate policy, have intensified interest in shifting from fuel to electricity in industry. However, as highlighted by recent analyses, Europe also faces structural disadvantages: higher electricity prices than most of its competitors, regulatory complexity, and slow permitting for renewables and grid expansion. Industrial electrification must therefore be designed not only at the equipment level, but also with a system perspective that accounts for grid integration, flexibility, and investment frameworks.

Against this backdrop, the e-CODUCT project proposes to electrify a key chemistry building block: the production of carbon monoxide (CO) from waste CO₂ and H₂S in an electrothermal fluidised bed reactor. CO is a versatile platform molecule for downstream synthesis (e.g. of methanol, acetic acid, oxo-alcohols) and its production via electrified, circular routes can substantially reduce emissions along multiple value chains.

CURRENT STATUS OF INDUSTRIAL ELECTRIFICATION

Industrial electrification has progressed from concept to pilot and, in some cases, early demonstration. Key trends can be summarised along three dimensions, i.e., technology readiness, system integration, and policy and market drivers.

Technology readiness: Electrified high-temperature processes are moving forward on several fronts. Electrified steam cracking concepts for ethylene production have been proposed and are under development by consortia of major chemical producers and equipment vendors.² Electrified reformers for hydrogen production (e.g. electrically heated steam-methane reformers or all-electric e-reformers) are being studied as alternatives to conventional fired furnaces.⁷ In parallel, electrified catalytic reactors based on induction heating have demonstrated significant improvements in activity and selectivity for reactions such as catalytic methane decomposition, CO₂ methanation, NH₃ cracking, CO oxidation, and hydrocarbon reforming.^{6,9} These systems can achieve fast start-up times and high heating efficiencies, making them suitable for flexible operation.^{5,9}

System integration: Techno-economic and environmental assessments of electrifying large (petro)chemical units highlight both the potential and the constraints. In an ethylene plant case study where natural-gas-fired boilers are replaced with electric boilers powered by renewables, different

configurations of concentrated solar power (CSP), photovoltaic (PV) and wind power have been evaluated.⁴ Land availability emerges as a key constraint, especially for wind, which has the largest footprint among the three options. The investigation also assesses hybrid solutions and imported clean electricity, exhibiting how trade-offs between cost, land use, and emissions must be balanced at the system level.^{4,7}

Policy and market drivers: Climate targets (e.g. net-zero by mid-century), carbon pricing, and emerging regulations on product carbon footprints are creating long-term incentives for industrial electrification. Simultaneously, the competitiveness of energy-intensive industries depends on electricity price levels, grid reliability, and access to low-carbon power.^{1,5,7} Analyses of the European context emphasise that, although the continent has profound scientific and technological capabilities, structural issues such as high energy costs, fragmented regulation, and slow infrastructure development can delay the deployment of electrified solutions.¹ Overcoming these barriers requires coordinated policy frameworks, risk-sharing mechanisms for first-of-a-kind projects, and planning that links industrial sites with renewable energy and grid expansion strategies.^{5,7}

ELECTRIFICATION TECHNOLOGIES

A range of electrification technologies can be deployed in (petro)chemical processes, each with distinct characteristics, strengths, and limitations.

Resistive (Joule) heating: An electric current is sent through a conductive/resistive element (e.g. a tube, plate, or structured catalyst support), generating heat directly within this material. This approach is conceptually simple and can be retrofitted into existing equipment (for example, replacing gas-fired coils with electrically heated tubes).^{7,8} Joule heating allows for rapid temperature changes and precise control but requires materials capable of withstanding high temperatures and thermal cycling.⁸ It is well suited to plug-flow or tubular reactors and to applications where uniform heating is more important than localisation.⁸

Induction heating (IH): Alternating electromagnetic fields are used to induce Eddy currents and magnetic losses in conductive or magnetic materials, converting electrical energy into heat directly within the catalyst or support.^{6,9} In catalytic systems, IH can deliver highly localised heating at the particle or bed scale, minimising the heating of the gas phase and surrounding hardware.^{6,9} Investigations have shown that IH can significantly enhance catalytic performance compared to conventional convective heating - not only due to better control of temperature and hot-spot formation, but also through possible non-thermal effects of oscillating magnetic fields on radical species, adsorption-desorption equilibria, and defect-mediated reactions.⁶ For carbon-based catalysts, IH has enabled efficient catalytic methane decomposition and plastic-to-olefin upcycling, with the as-formed carbon acting as an active phase rather than a deactivating deposit.^{6,9}

Microwave heating (MW): This type of heating relies on the interaction of electromagnetic waves at GHz frequencies with polar molecules or conductive solids. It can lead to volumetric heating and the formation of micro-scale hot spots, particularly in heterogeneous catalysts with selective absorption.⁷ MW-assisted processes have been explored for hydrogen production, CO₂ reduction, and organic transformations.⁷ As with IH, the combination of high heating rates, localised energy deposition, and potential non-thermal effects can improve selectivity and energy efficiency. However, reactor design and scale-up remain challenging due to complex field distributions and penetration depth limitations.⁷

Electrocatalytic processes: Beyond thermal methods, electrochemical processes such as water electrolysis, CO₂ electroreduction, and membrane-based separations directly convert electrical work into chemical transformation.⁷ In the context of (petro)chemicals, the most relevant process today is water electrolysis for hydrogen production, which underpins power-to-methanol, power-to-ammonia, and other e-fuels.⁷ Electrochemical CO₂ reduction is an active research field, but not yet at industrial

scale for bulk chemicals. Electrochemical routes can, in principle, offer very high selectivity and process intensification, but require substantial advances in durability, scaling, and integration into existing plants.⁷

Heat pumps and hybrid systems: For lower-temperature process heat (below ~200–250 °C), high-efficiency heat pumps can provide heat with coefficients of performance (COP) between 3 and 5 or more.⁷ In (petro)chemicals processing, such temperature levels are less central than in food or pulp and paper, but there are still opportunities in utilities and low-temperature sections.⁷ Hybrid systems combining heat pumps, electric boilers, and thermal storage can improve overall energy efficiency and reduce peak loads on the grid.⁷

Overall, the choice of electrification technology must consider temperature requirements, reactor type, catalyst properties, grid interaction (flexible vs. baseload operation), and integration with upstream and downstream units. Induction and Joule heating appear particularly promising for high-temperature (petro)chemical applications and in particular for the e-CODUCT ElectroThermal Fluidized Bed (ETFb) reactor concept.

(PETRO)CHEMICAL SECTOR STATUS

Electrifying (petro)chemical production involves re-thinking both utilities (steam and power) and core process units.

Utilities and steam networks: In a representative ethylene plant, steam is generated by cooling cracked gas, supplemented by natural-gas-fired boilers. Superheated steam drives major compressor trains (cracked gas, propylene, ethylene), and medium- and low-pressure steam is used throughout the plant. When the fired boilers are replaced with electric boilers and the steam network is re-balanced, the plant's direct fuel consumption and associated CO₂ emissions decrease substantially, but the electricity demand increases by tens of megawatts.⁴ To decarbonise this new electrical load, CSP, PV, and wind options have been evaluated.⁴ Wind achieves the lowest LCOE (~0.081 USD/kWh), PV is slightly more expensive (~0.09 USD/kWh), and CSP has the highest cost (~0.237 USD/kWh) due to important CAPEX contributions, but with the advantage of producing both power and steam and offering intrinsic storage.³ Land requirements, however, are substantial: several tens of thousands of square metres for CSP and PV, and even more for wind when spacing constraints are included.⁴

Core process units: Beyond utilities, core units such as steam crackers, reformers, and synthesis reactors can be directly electrified. Electrified steam crackers aim to replace fuel-fired radiant coils with electrically heated ones, potentially reducing furnace size and improving heat transfer.² Electrified reforming and partial oxidation units can be integrated with electrolysis-based hydrogen production, enabling low-carbon syngas for methanol, oxo-alcohols, and other downstream products.⁶ Electrified catalytic reactors, especially those based on IH, have demonstrated that carbon deposits can transform from a liability into an asset: in catalytic methane decomposition operated under IH, the carbon formed during the reaction becomes a graphitic, conductive layer that participates actively in catalysis and enhances heat transfer, instead of passivating the surface as in conventional heating.^{6,9}

Circular-economy opportunities: Electrification supports circularity in several ways. First, electric power allows process operation closer to renewable generation sites (e.g. co-location with large wind or solar resources), reducing energy transport requirements. Second, electrified reactors can be designed to utilise waste CO₂ and sulphur-containing streams as feedstocks, as in the e-CODUCT concept. Third, the ability to operate flexibly with the grid opens the door to valorising surplus renewable electricity as chemical energy (power-to-chemicals), thus coupling electricity and materials systems.

Challenges: Despite these opportunities, several challenges remain. High capital expenditure (CAPEX) for first-of-a-kind electrified units, uncertainties around long-term electricity prices, and the need for

significant grid reinforcements can slow adoption.^{1,5,7} Furthermore, retrofitting existing (petro)chemical complexes requires careful planning to manage downtime and integration risks.⁷ In some regions, electricity remains more expensive than natural gas on an energy basis, weakening the short-term business case with the absence of strong carbon pricing or targeted support mechanisms.^{1,7}

METHANOL ELECTRIFICATION CASE STUDY

Methanol is a central platform chemical used in production of formaldehyde, acetic acid, methyl *tert*-butyl ether (MTBE), dimethyl ether (DME), and is a potential energy carrier and e-fuel. Conventional methanol plants rely on syngas produced via steam-methane reforming (SMR) or autothermal reforming (ATR) of natural gas, followed by catalytic synthesis over Cu/ZnO/Al₂O₃ at 50–100 bar and 200–280 °C. The dominant emissions arise from fuel combustion in the reformer and from process CO₂.

Electrified methanol pathways replace fossil-based syngas with H₂ from water electrolysis and CO₂ captured from industrial sources, biogenic streams, or direct air capture. In a simplified picture, the methanol synthesis step remains similar, but the upstream syngas generation becomes a power-to-X process. The total electricity demand is dominated by electrolysis (typically 50–55 kWh/kg H₂ for current commercial alkaline and PEM systems), with additional electricity required for CO₂ capture, compression, and process auxiliaries.⁷

A representative electrified methanol system can be characterised as follows:

- Feedstocks: CO₂ (from industrial flue gas or biogenic sources) and water.⁷
- H₂ supply: dedicated electrolyzers co-located with the plant, sized to match the methanol output and CO₂ availability.⁷
- Heat integration: waste heat from compression and synthesis can be used for CO₂ regeneration or district heating; resistive or induction heating can supplement where needed.^{7,9}
- Electricity supply: mixture of on-site renewables (e.g. wind, PV) and imported low-carbon electricity, depending on land and grid constraints.^{4,7}

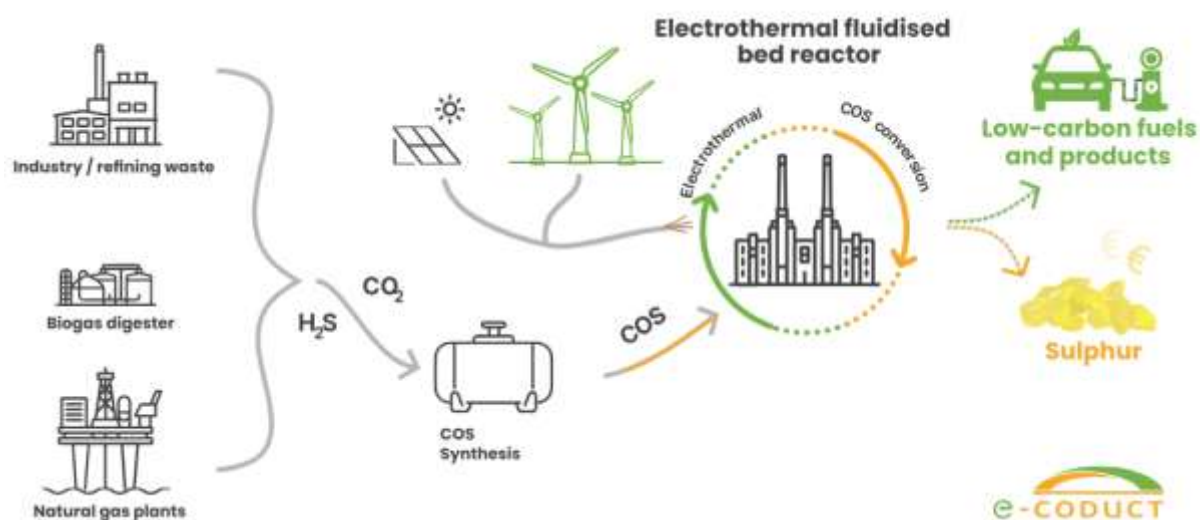
Compared to a conventional natural-gas-based plant, the electrified methanol route can reduce direct CO₂ emissions by more than 90% when supplied with low-carbon electricity and CO₂ of biogenic or atmospheric origin.⁷ The levelized cost of methanol is highly sensitive to the electricity price and electrolyser CAPEX and efficiency.⁷ At electricity prices in the range typically projected for large-scale renewables in high-resource regions, and assuming continued cost reductions in electrolyzers, green methanol can become competitive in markets where low-carbon products command a premium or where carbon pricing internalises the climate impact of fossil products.^{1,7}

This case study is conceptually analogous to the ethylene electrification analysis discussed earlier: in both cases, high-temperature fossil-based process steps are replaced by electric alternatives, and renewable electricity becomes the main energy input. For e-CODUCT, which targets CO as a platform molecule, the methanol case illustrates how an electrified CO source can plug into downstream synthesis, enabling a fully electrified CO₂-to-methanol chain.

THE E-CODUCT PROPOSITION

e-CODUCT focused on designing, building, and validating an ETFB reactor for the production of CO from waste CO₂ and H₂S, powered by renewable electricity. Within the broader electrification landscape described above, e-CODUCT can be seen as a bridging technology between upstream decarbonised power and downstream low-carbon chemicals.

Technological concept: In the ETFB reactor, solid particles (e.g. catalyst or catalytic support) are fluidised by a gas stream containing COS, generated by converting CO₂ and H₂S. Electrical energy is delivered directly into the bed - through resistive heating - creating a highly controllable thermal environment.^{6,8,9} Catalyst formulations are tailored to promote selective formation of CO from the decomposition of COS, while managing sulphur species and minimising undesired by-products. Because the bed is electrothermally heated, there is no need for external gas-fired furnaces, and the reactor can, in principle, respond quickly to changes in power availability.^{5,7}



Scheme 1: Schematic of the e-CODUCT project integration.¹⁰

Integration into (petro)chemical value chains: CO produced in the ETFB reactor can be used as a platform molecule for a suite of downstream processes: synthesis of methanol (via CO/CO₂/H₂ mixtures), acetic acid (via methanol carbonylation), oxo-alcohols, phosgene substitutes, and other carbonylation chemistries. When combined with green hydrogen and appropriate purification, e-CODUCT can feed into fully electrified power-to-liquids value chains. Using waste CO₂ and H₂S as feedstocks further supports site-level circularity by valorising streams that would otherwise be treated as liabilities.

Alignment with system-level trends: e-CODUCT addresses several of the challenges highlighted in recent analyses. First, it targets electrification of a high-temperature, high-value-added unit operation where electric heating can deliver both efficiency and process-intensification benefits.⁷⁻⁹ Second, by converting waste CO₂ and H₂S, it reduces the need for separate end-of-pipe abatement systems and helps (petro)chemical sites meet increasingly stringent emissions and sulphur-management regulations.^{1,7} Third, the modular nature of fluidised-bed reactors and their compatibility with fast electrical heating make the concept suitable for flexible operation, enabling coupling to variable renewable electricity rather than relying solely on baseload power.^{5,7}

Collaboration and scaling: e-CODUCT is connected to a group of sister projects exploring complementary aspects of electrification and CO₂ utilisation. This collaborative network is critical to accelerate learning across materials, reactor concepts, system integration, and techno-economic assessment.^{1,7} As demonstration progresses, the project can provide empirical data on performance (energy efficiency, CO selectivity, stability, operability) under realistic industrial conditions, informing both future scale-up and policy discussions around support mechanisms for industrial electrification.^{5,7}

CONCLUSIONS AND PERSPECTIVES

Industrial electrification is moving from concept to deployment in the (petro)chemical sector, with early large scale demonstrations (e.g. electrically heated cracking) and a rapidly expanding body of work on electrified reactors and system integration.^{4,6-9} The technical case is increasingly clear: replacing fossil-fired heat with low carbon electricity can deliver deep emissions reductions and new operating modes, but the pace of rollout will be determined as much by power system conditions (renewable build out, grids, flexibility and permitting) and investment de-risking as by equipment performance.^{1,2,5,7}

From this perspective, four priorities emerge:

- Scale near-term electrification where it is already bankable (utilities, steam systems, and first-of-a-kind high temperature units), while using demonstrations to reduce perceived technology and integration risk.^{4,7}
- Design for power system reality, including flexible operation, thermal/electrical buffering and plant-wide integration, so electrified units can follow variable renewable supply without undermining product quality or safety.^{2,5,7}
- Accelerate reactor and catalyst innovation (Joule/induction heated concepts, tailored catalyst supports, and intensified contactors) to reduce energy losses and enable new process windows at industrially relevant scales.^{6,8,9}
- Use electrification to unlock circular feedstocks by coupling low carbon power with CO₂ and sulphur stream valorisation; here, e CODUCT's ETFB reactor approach provides a concrete pathway to convert waste CO₂/H₂S into CO as a platform molecule for downstream synthesis.^{1,6-9}

For e-CODUCT, the immediate perspective is to translate this alignment into quantified evidence—stable operation, selectivity, energy efficiency and operability under dynamic power input—so that the concept can be assessed against competing CO pathways and positioned for scale up within integrated, electrified (petro)chemical hubs.^{2,4,5,7}

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