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Cost reduction analysis for sustainable ethylene production technologies

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ABSTRACT

Production of ethylene, one of the main petrochemicals, remains heavily dependent on fossil fuels, both as energy source and as feedstock. Several strategies and options are being considered to decarbonize and defossilize ethylene production. So far, no studies exist that provide quantitative insights into how to accelerate the development and deployment of new ethylene technologies. The aim of this work is to determine under which technological learning and market deployment conditions renewable ethylene production technologies can become cost competitive by 2050. To meet this goal, six new ethylene production technologies are analyzed: electric cracking, ethanol dehydration, oxidative coupling of methane (OCM), dimethyl-ether-to-olefins (DMETO), methanol-to-olefins (MTO), and CO_2 electrolysis. We find that renewable ethylene is 3–9 times more expensive than the current average market price of ethylene. A three-level framework (with technology, process, and system as dimensions) to analyze cost reductions is applied and nine different cost projections for 2050 based on different learning rates and deployment scenarios are shown. Feedstock prices as low as 230€/t are required, to achieve the most optimistic projected cost of ethylene produced via electric cracking of synthetic naphtha (480€/t). Ethylene produced from synthetic MTO could cost 1030€/t by 2050, contingent on a price of synthetic methanol of around 450-475€/t. Achieving a projected ethylene cost from OCM of 529€/t remains challenging, even with low synthetic natural gas prices and state-of-the art technology. Ethylene from CO_2 electrolysis has a projected cost of 1660€/t in 2050. Even with low electricity prices (5€/MWh) and state-of-the-art technology, this projection remains practically unattainable. Ethylene production from synthetic DMETO or synthetic ethanol dehydration does not achieve cost competitiveness in 2050, as the costs reach 1250€/t and 1100€/t, respectively.

Introduction

The petrochemical industry plays an important role in the energy transition, as around 14% of total primary oil demand, and 8 % of primary natural gas demand are currently dedicated to manufacture plastics, rubbers, synthetic fibers, insulating materials, and other chemicals [1]. The demand for these products is expected to increase because of economic growth, increasing global population, and improving living standards [1,2]. If current trends continue, the demand for fossil fuels by the petrochemical industry is expected to double by 2050. This would result in greenhouse gas (GHG) emissions that exceed the required limit to keep global average temperature below 1.5 °C [3].

Production of ethylene, one of the main petrochemicals, remains heavily dependent on fossil fuels, both as energy source and as feedstock. Several strategies and options are being considered to decarbonize and defossilize ethylene production. The International Energy Agency (IEA) proposes several mitigation options to reduce carbon dioxide (CO_2) emissions from ethylene production, such as improving energy and material efficiency, switching to natural gas as energy carrier and feedstock, and implementing CO_2 capture and storage (CCS) or CO_2

Abbreviations: CAPEX, capital investment cost; CIC, cumulative installed capacity; CO_2, carbon dioxide; CP, cumulative production; DMETO, Dimethyl ether-to-olefins; FE, faradic efficiency; Fixed OPEX, fixed annual cost of operation and maintenance; GHG, greenhouse gas; H_2, hydrogen; IEA, International Energy Agency; LC, learning curve; LR, Learning rate; MeOH, methanol; MMTA, million metric ton per annum; MTO, Methanol-to-olefins; OCM, Oxidative coupling of methane; TRL, Technology Readiness Level; Variable OPEX, variable annual cost of fuel and feedstock.

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capture and usage (CCU) systems. [1] Bio-based feedstock, plastics circularity, and recycling, as well as new technologies to produce ethylene from captured CO_2 and green hydrogen (H_2), might also play a role in reducing fossil fuel demand and GHG emissions from ethylene production [4].

Existing literature presents analyses of various technologies that could be used to decarbonize and defossilize ethylene production and focuses on identifying technological and economic challenges that must be addressed to make these alternatives cost-competitive. Chauhan et al. [5] report a production cost of 1950€/t of CO_2-based ethylene and discuss challenges and opportunities of achieving efficient and cost-effective production of ethylene via the development and deployment of electric cracking, electrochemical dehydrogenation of alkanes, and CO_2 electrolysis. Lamichhane et al. [6] plead for a small-scale decentralized production approach to test new technologies, such as oxidative coupling of methane (OCM), ethanol dehydration, electrochemical reduction of CO_2, photocatalysis, electro catalysis, biocatalysis, and plasma catalysis. Amghizar et al. [2] suggest technological improvements for methanol-to-olefins (MTO), Fischer-Tropsch synthesis, OCM, and catalytic dehydrogenation of light alkanes, and emphasize the need for global regulations to drive the adoption of these technologies. Layritz et al. [7] analyze the carbon and energy flows of electric steam cracking, and OCM fed with synthetic natural gas (produced from captured CO_2 and green H_2), and assess the impact of implementing these technologies in the European energy system. They conclude that given the current carbon intensity of the European electricity grid, neither option results in net emission reductions. However, both strategies have the potential to achieve emission reductions between -1.74 and -8.54 t CO_2(eq)/t ethylene. Nyhus et al. [8] report a cost for sustainable ethylene between 3500 and 6400€/t and identify key factors to achieve cost-competitiveness of nine different ethylene production routes. They also mention technical and system limitations of substituting steam crackers with renewable ethylene technologies, such as a high renewable electricity demand, and market dynamics. Zhao et al. [9] analyze the economic performance of twenty ethylene production pathways from fossil and renewable feedstock reporting production costs between 600 and 2600€/t. They conclude that most renewable ethylene production technologies are economically unattractive at present, when compared to the incumbent technology, and that only MTO fed with syngas from second generation biomass is reported to be cost competitive under the considered assumptions.

Currently, no studies exist that provide quantitative insights into how to accelerate the development and deployment of new ethylene technologies. Hence, the aim of this work is to determine under which technological learning and market deployment conditions renewable ethylene production technologies can become cost competitive by 2050. To reach this goal, six new ethylene production technologies were selected, considering relevance, data availability and technology maturity: electric cracking, ethanol dehydration, OCM, DME to olefins, MTO, and CO_2 electrolysis. A techno-economic analysis is undertaken with homogenized data found in the literature to determine the current production costs of ethylene through these six options. Considering ethylene demand projections reported by the IEA [1], three different scenarios are proposed to calculate how much ethylene is supplied by each technology by 2050. Lastly, potential cost reductions for each technology are projected. This is done by means of learning curves and following the three-level framework developed by Toribio-Ramirez et al. [10] that enables the study of cost reductions of industrial processes. The results from the present work help identify data gaps for the technical and economic performance of renewable ethylene production technologies. We also highlight the importance of having access to real and current engineering and building cost data, as covering these gaps would increase the robustness of the cost projections presented in the present work. For industrial stakeholders, we give insights into the next steps to follow in order to further develop the technologies presented in this study. Finally, we give specific targets for policymakers to bear in mind when developing policies to drive the adoption and deployment of renewable ethylene production technologies.

Section 2 explains the methods and materials used for analysis. The overall results are presented in Section 3. Section 4 presents the analysis and discussion of our results. A set of final remarks is presented in Section 5.

Methods and materials

Five steps are followed to determine under which technological learning and market deployment conditions renewable ethylene production technologies can become cost competitive by 2050.

a) **Literature review and technology selection**: A literature review using Google Scholar, was undertaken to determine a list of technologies to produce renewable ethylene. The key words 'green ethylene', 'decarbonization of ethylene', 'sustainable ethylene', 'bio-ethylene', 'decarbonization of light olefins' were used. A total of 1620 relevant studies from 2017 to 2024 were found. A non-exhaustive list of technologies was created with the technologies reported in the most relevant papers (See Table A in the Supplementary Information). Three criteria were applied to select the technologies to be analyzed in the present work.
   - Relevance: refers to the extent to which a technology is garnering attention. It is measured by the number of studies that report a certain technology as a potential option to substitute incumbent ones.
   - Data availability: refers to the ease with which data could be retrieved in open literature, and the completeness of information on the variables needed for the analysis. This is measured as a binary variable: 1 if both capital expenses and mass and energy balance data are available, or 0 if neither or just one is available.
   - Technology maturity: refers to the extent to which a technology has progressed from initial research and concept development to a fully functional, tested, and validated solution. It is measured by the Technology Readiness Level (TRL). A TRL close to 9 means that the technology is ready to be fully deployed, while a TRL between 5–6 refers to a technology in the pilot scale, and lower TRLs means that the technology is still at the lab scale.

b) **Technology description, data collection, and data quality assessment**: We searched for techno-economic data for the selected technologies, focusing on state-of-the-art performance, capital expenses, and reported performance improvements. Preference was given to data obtained from reports of experimental tests, clear process design and modeling literature, and techno-economic literature with a detailed break-down of all equipment costs, and a clear description of cost calculations.

c) **Techno-economic model**: we undertook a techno-economic analysis with homogenized data found in the literature to determine the current production cost of ethylene.

d) **Scenarios for future ethylene demand**: The adoption level of each technology from 2019 to 2050 was modeled with an S-curve. Three different scenarios were created to calculate how much ethylene is supplied by each technology by 2050. Scenario 'One takes all' assumes that in 2050 all ethylene demand is supplied by only one technology. The deployment of this new technology depends solely on the adoption level (S-curve). For the scenario 'Phase out', we assume a 1 % annual reduction of ethylene production from incumbent technologies, starting from 2024. New capacity requirements are covered with only one new technology. Typically, the combination of demand reduction, and the implementation of another technology is required, since one single technology might not be capable of immediately replacing naphtha and ethane cracking production. Scenario 'Joint supply' assumes that all six new technologies are used to produce renewable ethylene in 2050.

e) **Learning model and projected cost reductions**: potential cost reductions for each technology were projected. This is done by means of learning curves and following a three-level framework developed by Toribio-Ramirez et al. [10] that enables the study of cost reductions of industrial processes.

Literature review and technology selection

After a non-exhaustive review, a list of 16 different technologies was created that could be used to decarbonize and defossilize ethylene production (See Table A in the Supplementary Information). Considering the relevance, data availability, and technology maturity, the list was shortened to six technologies: electric cracking, ethanol dehydration, OCM, DMETO, MTO, and CO_2 electrolysis.

Fig. 1 compares the three commercial technologies with the technologies selected to be studied in the present work. There are currently three main commercial technologies to produce ethylene. The main technology is steam cracking of hydrocarbons. The feedstock is selected depending on availability and price. In the United States and Middle East, where natural gas is abundant and cheap, ethane is the preferred feedstock. In Europe and Asia, ethylene is mainly produced from naphtha. In recent years, due to rising oil prices and the vast amount of cheap coal available in China, ethylene has been produced from coal-derived methanol (MeOH) following the MTO pathway [11]. At smaller scales, ethylene is also produced via bio-ethanol dehydration in Brazil and India, where bio-ethanol is mainly produced from fermentation of sugars [12], yielding so-called first-generation bio-ethanol. For

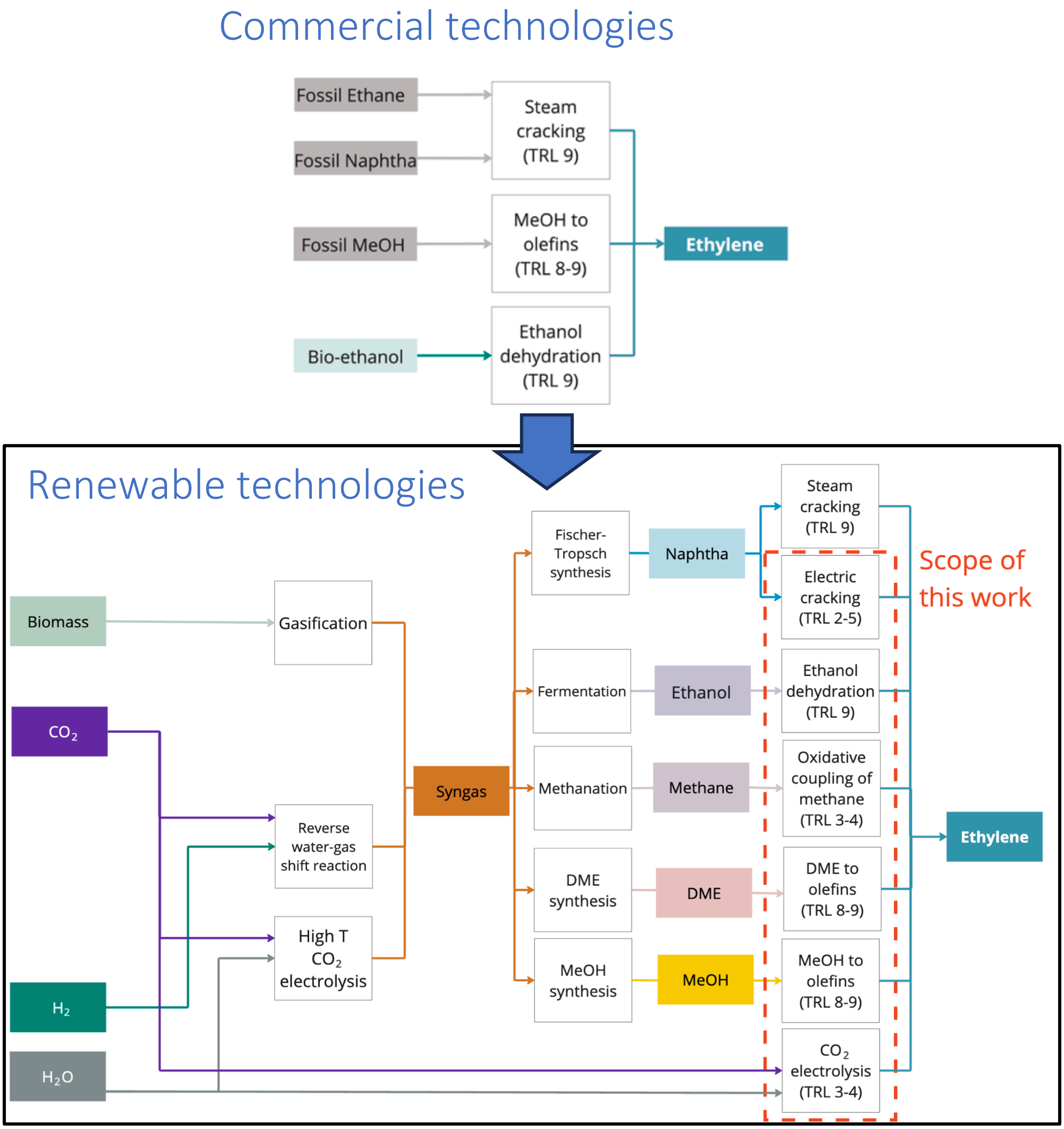


Fig. 1. Commercial and renewable technologies for ethylene production.

the new renewable technologies, the feedstocks used may be biomass or captured CO_2 in combination with green H_2. After several processing steps, these raw materials are converted into precursor chemicals which are used to produce ethylene. Depending on the feedstocks used and the technology selected, the production of ethylene may result in different economic requirements.

Technology description, data collection, and data quality assessment

Electric cracking

An option to reduce the GHG emission of the traditional steam cracking process is to electrify its heat demand. Tijani et al. [13] report several technologies to achieve this, such as using electrical resistance heating, inductive heating, dielectric heating, microwave, infrared, electric arc, and plasma. Theofanidis et al. [14] present an overview of electricity-driven steam crackers employing various heating technologies, reporting a 20 % increase in olefins yield for shockwave-heated crackers compared to conventional steam cracking, enhanced energy efficiency in hybrid tubular reactors integrating inductive and resistive heating, and a 30 % reduction in energy consumption with microwave heating. Compared to conventional cracking, electric cracking significantly reduces specific energy consumption by utilizing all applied heat for the cracking reaction. The specific energy consumption of conventional naphtha cracking is around 26–31 GJ/t ethylene [15], while the specific energy consumption of electric cracking is approximately 11 GJ/t ethylene [16].

The performance and techno-economic data found in literature for this technology is limited and quite uncertain. Shekunova et al. [17] report ethylene yields from cracking hydrocarbons with heat from an electrical current passing by tungsten, molybdenum, or nichrome metal coils. The highest ethylene yield reported is 46 % (See Fig. 2). Porsin et al. [18] optimize reaction conditions for acetylene synthesis produced via high-temperature methane pyrolysis powered by electrical resistance heating. Balakotaiah and Ratnakar [19] propose different reactor configurations with electrical resistance heating. Fig. 3 shows boxplots of the capital investment cost (CAPEX) data found in open literature. Oliveira Machado dos Santos et al. [20] report a capital investment cost between 23 and 50 $M€_{2018}$ for a 10 MW_{th} cracker. Gu et al. [21] report a CAPEX of 30 $M€_{2021}$ for both an electric and conventional cracker. No detailed process design could be found in open literature.

Electric cracking needs to be further developed to be applied on a larger scale. The IEA [12] reports a TRL of 5 for electric resistance heating crackers. Currently, there are plans to make a demonstration ethylene plant in Ludwigshafen (Germany) with a capacity of 6 MWe, which will serve as a proof of concept [22]. Furthermore, electricity-driven steam crackers face challenges for large-scale implementation, including the availability of renewable electricity, the intermittency of power supply, and the complexity of retrofitting existing infrastructure. Spillovers from other sectors (e.g. electric resistance heating in home appliances) and other industrial scale electric crackers (e.g. the Huels and the DuPont reactors to produce acetylene) might help to speed up the technological development [13].

Ethanol dehydration

Using biomass as an alternative feedstock is another option to reduce the GHG emissions from ethylene production. Commercial scale plants are located in Brazil (with an ethylene capacity of 0.2 million metric ton per annum (MMTA)), and in India (0.175 MMTA). Two dehydration

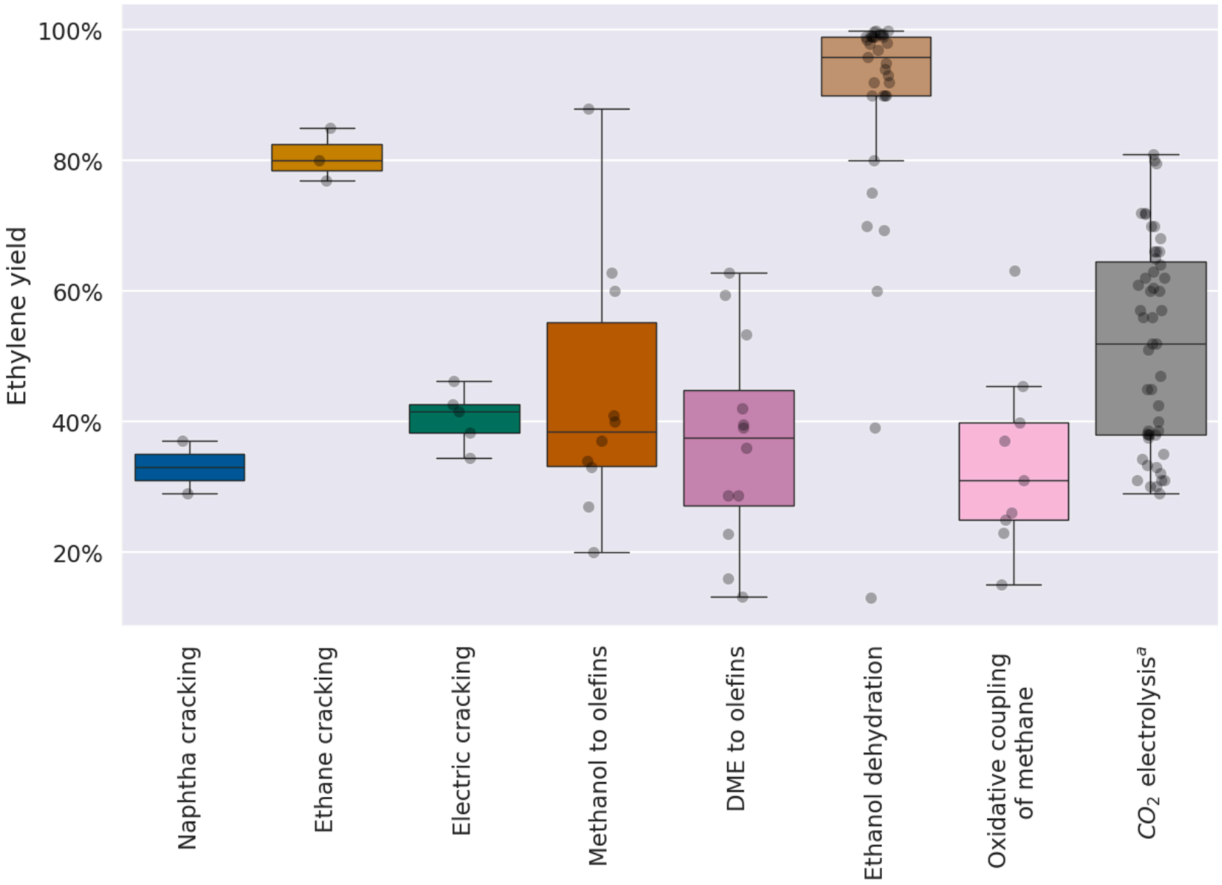


Fig. 2. Box-plots of yields reported in literature. [a] For CO_2 electrolysis, data for Faradic Efficiency (FE) is shown. Sources: naphtha cracking and ethane cracking [9,15], electric cracking [17,60], methanol to olefins [43–46], DME-to-olefins [36,37,44], ethanol dehydration [9,24,25,27], oxidative coupling of methane [9,33,34], CO_2 electrolysis [54–57].

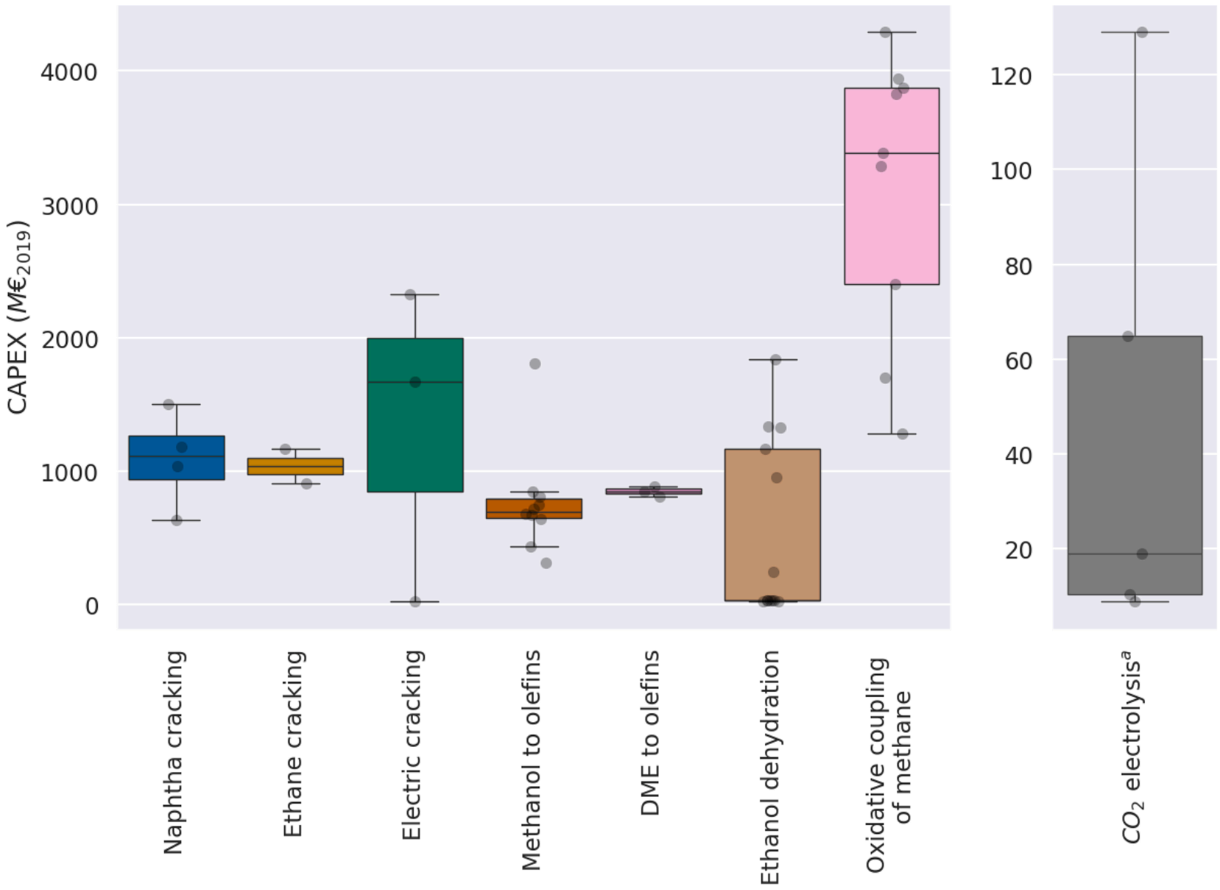


Fig. 3. Box-plots of CAPEX reported in literature. ^{a} For CO_2 electrolysis, data for 10 MW_e capacity is shown. Sources: naphtha cracking [1,35,47,61], ethane cracking [61], electric cracking [21,60], methanol-to-olefins [1,43,47,60], DME to olefins [38,39], ethanol dehydration [1,26,28,29,38,39], oxidative coupling of methane [33,35], CO_2 electrolysisy [54,56–58].

technologies have been commercialized. The catalyst and process design called Atol ^{TM} functions with two fixed-bed adiabatic reactors and produces between 0.05 and 0.4 MMTA of ethylene. Hummingbird ® is a proprietary process developed by British Petroleum (BP), with multiple fixed-bed reactors connected in series. This is an established technology, hence a TRL level of 9 is given [12].

The performance and economic data for this technology have a high degree of variability. Jermolovicius et al. [23] report a yield of 61 % if the heat for the reaction is supplied via microwave heating. Both Fan et al. [24] and Jamil et al. [25] report the performance of different catalysts, reaction conditions, and reactor technologies that have achieved high ethylene yield. The highest ethylene yield reported is 99.9 % (See Fig. 2). Zhao et al. [9] report a yield of 53 % and a CAPEX of 630€$_{2018}$ for a 0.4 MMTA plant. Depending on the route and capacity, Haro et al. [26] report a CAPEX between 6.1 M€$_{2014}$ and 447 M€$_{2014}$. The IEA reports a CAPEX of 1328 €$_{2016}$ for a 1 MMTA plant. Both Cameron et al. [27] and DSM et al. [28] analyze the competitiveness of bio-ethylene in Brazil and report, respectively, a CAPEX of 70 M€ and 200€$_{2016}$ for a capacity of 1 MMTA. Mohsenzadeh et al. [29] report a CAPEX of 11.2 M€$_{2015}$ for a capacity of 0.18MMTA (See Fig. 3). This variability arises due to differences in underlying assumptions and methodologies employed.

Oxidative coupling of methane

Switching to natural gas and implementing CCS systems are other options to reduce GHG emissions from ethylene production. OCM is a direct route to convert methane into ethylene. The OCM reaction occurs in two stages. First the C-H bonds of methane are broken at temperatures between 750 and 900 °C and ethane is formed. Then, ethane is converted to ethylene via oxidative dehydrogenation. These reactions have both thermodynamic and kinetic challenges. First, high temperatures are needed to break the C-H bonds from methane. Second, undesired byproducts such as CO_2, CO, and coke are more thermodynamically favored than ethylene. Third, because the OCM process is an exothermic reaction, hot-spots in the reactor are formed if there is no effective thermal management system. These high temperature areas increase the formation of by-products and negatively affect the ethylene yield. Fourth, the formation kinetics of the undesired by-products are faster than those of ethylene [30,31].

Several publications report experimental and modelling results from different strategies to overcome technological limitations of OCM. Zhao et al. [9] report yields of around 15–25 %. Ortiz-Bravo et al. [30] document various reaction conditions and catalyst performances, with the highest reported yield ranging between 23 % and 26 %. They suggest new reactor configurations that have a better oxygen distribution and heat management, which may reduce hot-spots and increase ethylene yields. The highest experimental yield reported is 39 %, with a membrane reactor. After studying the techno-economics of different configurations by means of computer simulations, Cruellas et al. [32] report a minimum yield between 25 and 30 % for the technology to be cost competitive. In a later work [33], they study the performance of membrane reactor designs and report a yield as high as 63 % (See Fig. 2). However, these results have not been validated with experiments. Godini et al. [34] analyze the technical and economic potentials of integrating OCM with methane reforming, where the unwanted byproducts are used to reform the unreacted methane. They report an overall yield of 35 %. These results were obtained from experimental tests performed in a mini-plant scale OCM facility constructed at the Berlin Institute of Technology, on the basis of which a TRL level of 3–4 is given to this technology.

Techno-economic data for this technology is well documented. Spallina et al. [35] study the techno-economics of the OCM process with five different heat management configurations and concluded that low ethylene yields hinder the cost competitiveness of this technology. This is mainly because an expensive separation train with high energy requirements is needed. Cruellas et al. [33] report the costs of two different OCM process schemes with membrane reactors. Fig. 3 shows the capital expenses reported for each configuration.

DMETO

Knowing that catalyst SAPO-34 has a good performance to convert methanol to light hydrocarbons, further research was performed to determine if this catalyst could be modified to produce olefins from DME. DME is typically produced via methanol dehydration. However, it can also be directly synthesized from bio-based feedstock or CO_2 and green H_2. In the DMETO process, DME is fed to a reactor where it is catalytically converted into light olefins. This reaction occurs over a solid acidic catalyst at elevated temperatures and moderate pressures. Next, the product flow is further separated and purified.

Performance and techno-economic data found in literature are shown in Fig. 2 and Fig. 3, respectively. Cordero-Lanzac et al. [36] report ethylene yields around 40 % after developing a kinetic model with data obtained from experimental runs. The Dalian Institute of Chemical Physics developed a variation of the SAPO-34 catalyst, which is called DO123 catalyst. In 1995 this catalyst was tested in a pilot plant. High catalyst activity and selectivity to light olefins was reported, and an ethylene yield of 50–63 % was achieved [34]. Good performance has also been achieved with other catalysts, like HZSM-5. Bakare et al. [37] study conversion of DME to olefins using a modified aluminum rich H-ZSM-5 catalyst and report ethylene yield around 13–36 %. Limited techno-economic literature was found with clear assumptions, including mass and energy balance, utility requirements, equipment cost and total investment cost. Haro et al. [38] report a fixed capital investment around 270 M€$_{2010}$ for a DMTO plant that produces 116 kt ethylene per year. Uslu et al. [39] report similar investment costs.

Considering that DMETO has benefited from experience gained from MTO processes, a TRL level of 8–9 is given to this technology. Further research might focus on identifying catalysts with higher activity, stability, and selectivity towards the desired products, improving the reactor design and optimizing operating conditions to increase product yield, enhance mass and heat transfer, and minimize catalyst deactivation [40].

MeOH-to-olefins

MTO has been mainly deployed in China, where coal is used to produce methanol. The first report of a MeOH-to-hydrocarbons process appeared in the 1970′s by Mobil Corporation [41]. In 1990, the Dalian Institute of Chemical Physics reported the synthesis of light olefins from methanol with catalyst SAPO-34. Several experiments on a demo-plant with a capacity of 16 kt MeOH per year were carried out in 2006. The effect of different operation parameters (e.g. gas catalyst contact time, temperature, etc.) on methanol conversion and light olefins selectivity was studied. In 2010 the first DME/MeOH-to-olefin (DMTO) industrial scale plant (1800 kt methanol per year) commenced operation. Further developments, for instance to improve the olefins yield, resulted in the second (DMTO-II) and third (DMTO-III) generations of the technology. At the end of 2014, the first DMTO-II commercial plant was started, while in 2018 the pilot plant experiments of the DMTO-III technology were finalized. Licenses to build and operate 26 new DMTO plants in China were distributed at the end of 2019 [42]. However, if the goal is to reduce GHG emissions, feedstocks like biomass or CO_2 and green H_2 are needed to synthesize methanol. This green methanol can be used as feedstock to produce propylene and ethylene.

The techno-economics and performance of this technology are extensively documented in literature. Fig. 2 shows ethylene yields reported. Chen et al. [43] consider an olefin yield of 33 % for a MTO process design that employs the SAPO-34 catalyst. Liu et al. [44] present pilot plant test results, reporting various ethylene yields between 20 % and 63 %. Continuous R&D efforts have resulted in the optimization of SAPO-34 catalysts, achieving ethylene yields between 60 % and 88 % [45]. Novel catalysts, such as SiO_2-Al_2O_3 are being developed, achieving an ethylene yield between 20 % and 41 % [46]. Fig. 3 shows the CAPEX reported in literature for this technology. The IEA [1] reports a CAPEX of 1000$\$_{2016}$ per t of olefins. Chen et al. [47] estimate an average CAPEX of 670 M€ for a MTO plant with an ethylene capacity of 1 MMTA. After a process design and economic analysis, the costs of an industrial scale UOP/Hydro MTO plant are calculated to be 300 M€ for a capacity of 370 kt ethylene per year [43].

There are four different MTO technologies available on the market: DMTO/ DMTO II/DMTO- III [42,48 49]Sinopec-MTO [50], MTO by UOP/Hydro [51], and MeOH-to-propylene by Lurgi [52]. Sinopec-MTO has a patented SAPO-34 catalyst that allows to change the share of propylene or ethylene in the product stream [53]. UOP/Hydro built a demonstration plant in Norway with a low-pressure fast fluidized-bed reactor [45], which can achieve a selectivity of 70–80 % to light olefins [51]. Two UOP/Hydro MTO plants exist in China, one with a capacity of 0.8 MMTA and the other with a 0.3 MMTA capacity [53]. Out of the four MTO technologies, DMTO has currently the largest market share in China. A TRL of 9 is attributed to this technology. Further development of this technology mainly focuses on addressing the rapid catalyst deactivation due to coke formation.

CO_2 electrolysis

Electrochemical reduction of captured CO_2 fits within the CCU options for reducing GHG emissions from industry. Water and captured CO_2 are fed into a low-temperature membrane electrolyzer, which can produce multi-carbon products, such as ethylene. There are two types of electrolysis reaction: liquid-phase and gas-phase. The first uses an aqueous solution to transport the CO_2 into the electrolyzer, where it reacts with the catalyst in the cathode compartment and is converted into ethylene. In a gas-phase reaction, CO_2 is directly fed into the electrolyzer, which at the cathode side has a gas diffusion electrode with a gas diffusion and catalytic layer. The CO_2 moves through the gas diffusion layer and is converted into ethylene by the catalyst. The product flow is then fed to a separation and purification step, where pure ethylene is obtained [54,55].

Fig. 2 shows values for faradic efficiency (FE) towards ethylene reported in literature. Lee at al. [55] review the performance of CO_2 conversion to ethylene using various catalysts and electrolytes and report an average FE of 57 %. Other sources report FE between 38–80 % [56], and of 64 % [54]. Shin et al. [57] report a FE as high as 81 %. Fig. 3 shows the CAPEX values reported in literature range between 8.9 M€$_{2019}$ and 129 M€$_{2019}$ for a 10 MW_e electrolyzer [54,56–58].

Currently, the selectivity towards C_2 hydrocarbons is too low for this technology to be considered for industrial purposes [55]. Research and development efforts are mainly focused on deepening the fundamental knowledge on catalysts and electrode materials, as well as reaction and diffusion mechanisms. This research is mainly performed at the laboratory scale, which justifies a TRL level of 3–4 for this technology [59] This technology faces challenges from the chemical and process engineering fields. From a chemical standpoint, improvements in FE and overpotentials are required to improve the overall energy efficiency. Such improvements require an active, stable, and selective catalyst as well as a deeper understanding of the reaction mechanisms. From an engineering perspective, a proper reactor design that optimizes mass transportation, process stability, ion conductivity, and heat management is required to enable electrochemical ethylene production at an industrial scale [59]. Shin et al [57] perform a waterfall analysis to show how improvements in the process may result in lower production costs. Further research is needed to determine the durability and stability of the electrolyzer operating under industrial conditions. Electrochemical

CO_2 reduction to ethylene can benefit from spillovers from other electrochemical processes. For example, the chlor-alkali industry can provide insights into the construction and operation of industrial-scale electrochemical installations. Also, large-scale demonstration projects of electrochemical reduction of CO_2 to CO or formic acid can provide insights into design, scale-up, and operation, which might help to speed up the technological development of ethylene production through a CO_2 electroreduction process.

Techno-economic model

The levelized cost of light olefins (ethylene and propylene) was calculated following Equation (1). To ensure that the results are comparable, all values are reported in $€_{2019}/t$. A capacity of 10 MW_e was assumed from CO_2 electrolysis, while an annual ethylene production capacity of 1 MMTA was used for the other technologies. For technologies that also produce propylene (naphtha cracking, ethane cracking, electric cracking, MTO, and DME-to-olefins), the mass balances in the Supplementary Information were used to calculate the propylene yields and determine the annual olefins production. Price allocation factors are calculated following Equation (2). We consider historical market prices for ethylene and propylene. A value of 1000 $€_{2019}/t$ of ethylene and 766 $€_{2019}/t$ of propylene was assumed. The levelized cost of ethylene can be determined by multiplying its allocation factor by the levelized cost of olefins. The CAPEX is annualized by using the capital recovery factor (α), which is a function of the discount rate and the lifetime of the equipment. Assuming a discount rate of 10 % and a lifetime of 20 years, we use a capital recovery factor of 12 %. The fixed OPEX is assumed to be 2.5 % of the CAPEX.

$$LCO_{olefins} = \frac{\alpha CAPEX + FixedOPEX + VariableOPEX}{E} \quad (1)$$

where:

$LCO_{olefins}$ is the levelized cost of olefins ($€_{2019}/t$).

α is the capital recovery factor (%).

CAPEX is the capital investment cost ($€_{2019}$).

Fixed OPEX is the fixed annual cost of operation and maintenance ($€_{2019}/t$).

Variable OPEX is the variable annual cost of fuel and feedstock ($€_{2019}/t$).

E is the annual olefins production (t)

$$P_i = \frac{n_i x_i}{\sum n_i x_i} \quad (2)$$

where:

P_i is the allocation factor of (co)-product i.

n_i is the yield of (co)-product i for each technology.

x_i is the market price of (co)-product i

For each technology, several CAPEX values are reported in literature. To homogenize the values, we use Equation (3). The Chemical Engineering Plant Cost Index (CEPCI) was used to convert the plant construction costs to $€_{2019}$, and the scale-up factor correlation was applied to calculate the costs at the assumed capacity. Average exchange rates of $1USD_{2019} = 0.9€_{2019}$, and $1CNY_{2019} = 0.14\ €_{2019}$ were used when needed. In some sources, the CAPEX is directly reported, whereas in others, just the equipment cost is known. For the latter, ratio factors were used to determine the CAPEX (See Table B in the Supplementary Information).

In the current work, the mean of the homogenized values is used as the base case. The mean CAPEX for naphtha cracking is 1063 $M€_{2019}$, while for ethane cracking it is 925 $M€_{2019}$. The mean CAPEX for electric cracking is 1343 $M€_{2019}$, for MTO 770 $M€_{2019}$, and for DME-to-olefins 850 $M€_{2019}$. For ethanol dehydration a value of 544 $M€_{2019}$ is assumed. For OCM and CO_2 electrolysis, respectively, 3111 $M€_{2019}$ and 47 $M€_{2019}$ are assumed.

$$CAPEX = CAPEX_{ref}\frac{CEPCI_{2019}}{CEPCI_{ref}}\left(\frac{P}{P_{ref}}\right)^R \quad (3)$$

where:

$CAPEX$ is the capital investment cost (€2019).

$CAPEX_{ref}$ is the capital investment cost found in literature for a reference year and a reference capacity.

$CEPCI_{2019}$ is the Chemical Engineering Plant Cost Index (CEPCI) for 2019.

$CEPCI_{ref}$ is the Chemical Engineering Plant Cost Index for the reference year.

P is the capacity considered for this study.

P_{ref} is the reference capacity.

R is the scale-up factor, with a value of 2/3. For modular technologies (CO_2 electrolysis), we assume a value of 0.8.

The variable OPEX was calculated by first determining the feedstock and utility requirements per ton of olefins (See Tables C–J in the Supplementary Information). The processing steps to produce the precursor chemicals (e.g. methanol or ethanol) is beyond the scope of our study, therefore prices reported in literature of precursor chemicals were used to calculate the economic potential of each technology. Given the typical fluctuations in feedstock prices, the average of the price ranges reported was used for simplicity. A list of all prices assumed can be found in Table K of the Supplementary Information. Lastly, the feedstock and utility requirements were then multiplied by their respective average prices.

Scenarios for future ethylene demand

Historical ethylene demand from 2019 to 2022 was obtained from Statista [62]. To calculate the share of ethylene produced via ethylene dehydration, we use capacity data of existing first-generation bioethanol dehydration plants, reported by IRENA [63]. Shares of MTO are calculated according to data from the Dalian Institute of Chemical Physics [64] and the Deutsche Bank [65]. Data is given per ton of olefins, and we assume that 45 % of olefins produced via MTO corresponds to ethylene. We assume that all new plants operate at their nameplate capacity, and ethylene demand matches the installed capacity. In 2022, more than 90 % of the ethylene produced came from steam cracking. Approximately 5 % of the ethylene production came from MTO, and 1 % form bio-ethanol dehydration.

Any of the six technologies we consider in the present work could solely or jointly supply ethylene demand in the future. Following projections by the IEA [1], ethylene demand in 2030 and 2050 is 222 Mt and 328 Mt, respectively. We consider three different scenarios to calculate how much ethylene is supplied by each technology. Under scenario '***One takes all***', we assume that in 2050 all the ethylene demand is supplied by only one technology. The deployment of this new technology depends solely on its adoption level. For the existing MTO and ethanol dehydration capacity, a lifetime of 20 years and the starting operation year of each plant is considered to account for decommissioning and closure of old plants. For existing steam cracking plants, we assume that as the new technology takes over, the existing plants are shut-down. For the ***'Phase out'*** scenario, we assume a 1 % annual reduction of ethylene production from naphtha and ethane cracking, starting from 2024. Therefore, fossil ethylene supply reduces to 163Mt in 2030, and 133 Mt in 2050. We again consider a lifetime of 20 years for existing MTO and ethanol dehydration plants. New capacity requirements are covered with only one new technology. A demand reduction, or the implementation of another technology would thus be required, since one single technology might not be able to immediately replace naphtha and ethane cracking production. For the ***'Joint supply'*** scenario, instead of just one new technology covering all new demand, we consider that all six new technologies are used to produce renewable ethylene. In 2050, 41 % of ethylene is still produced via steam cracking of hydrocarbons, while the rest is distributed between the six new technologies. OCM, DMETO and MTO have 11 % share each, while ethanol dehydration produces 7 % of ethylene demand. The rest is divided equally between CO_2 electrolysis and electric cracking. Further explanation on the three scenarios can be found in the Supplementary Information.

Considering the ethylene produced by each technology each year, we calculate the total cumulative installed capacity (CIC) and cumulative production (CP) for each scenario. The CIC is the sum of cumulative capacity in the year t-1 and new capacity added in the year t. CP is defined as the sum of annual production over the period under study.

Learning model and projected cost reductions

Cost reductions are projected by means of a learning model. Conventionally, historical performance and experience data per technology is required to model a learning curve (LC). Since it was not possible to obtain such data, another approach was required.

In previous work [10], a three-level framework was proposed to study technological learning of low-carbon industrial processes. By applying this framework, one can, jointly or individually, study cost reductions at the technology, process or system level. Fig. 4 shows the steps followed to apply the framework. First, from the 3-level framework, one needs to select the level one wants to study. The second step is to select the factors one wants to study at each level. Next, we select a parameter from the techno-economic model to act as proxy to represent the selected factors. Then, we model the learning effect on the selected proxy by means of an LC. Finally, we use the techno-economic model to calculate the levelized cost after learning.

We model cost reductions for ethylene produced via electric cracking, MTO, OCM, CO_2 electrolysis, DMETO, and ethanol dehydration. Because naphtha and ethane steam cracking are well established technologies in the market, we assume that no significant learning is taking place. Hence, no LCs are determined for these two options. Some technologies have no propylene as co-product; therefore, the LCs are constructed just for ethylene production costs. This is done to ensure comparability. To the best of our knowledge, learning rates (LRs) for most of these processes have not been reported in literature. Detz et al. [54] report LRs for different CO_2 electrolysis systems.

Learning at the technology level

At the technology level, we investigate the learning effect driven by guidance of the search (Factor 1), learning-by-searching (Factor 2), and technological spillovers (Factor 3). Guidance of the search refers to the degree to which expectations and support converge toward a specific technological development goal. Learning by searching includes all research and development activities to acquire new knowledge and capabilities, and technological spillovers refer to the unintentional sharing of knowledge, innovations or technologies benefiting others without a cost. We assume that thanks to these three factors, the yield improves by a fixed percentage with each doubling of the CP. To model this, Equations (4) and (5) are used for the feedstock requirements of each technology. LRs for efficiency improvements in industrial processes have been reported to be between 1 and 5 % [66]. After learning occurs, less feedstock is required to produce the same amount of ethylene. This positively impacts the variable cost when calculating the levelized cost.

$$Y_i = Y_o{}^{*}\left(\frac{X_i}{X_o}\right)^b \tag{4}$$

where:

Yi is the feedstock requirements after learning.

Yo is the initial feedstock requirements.

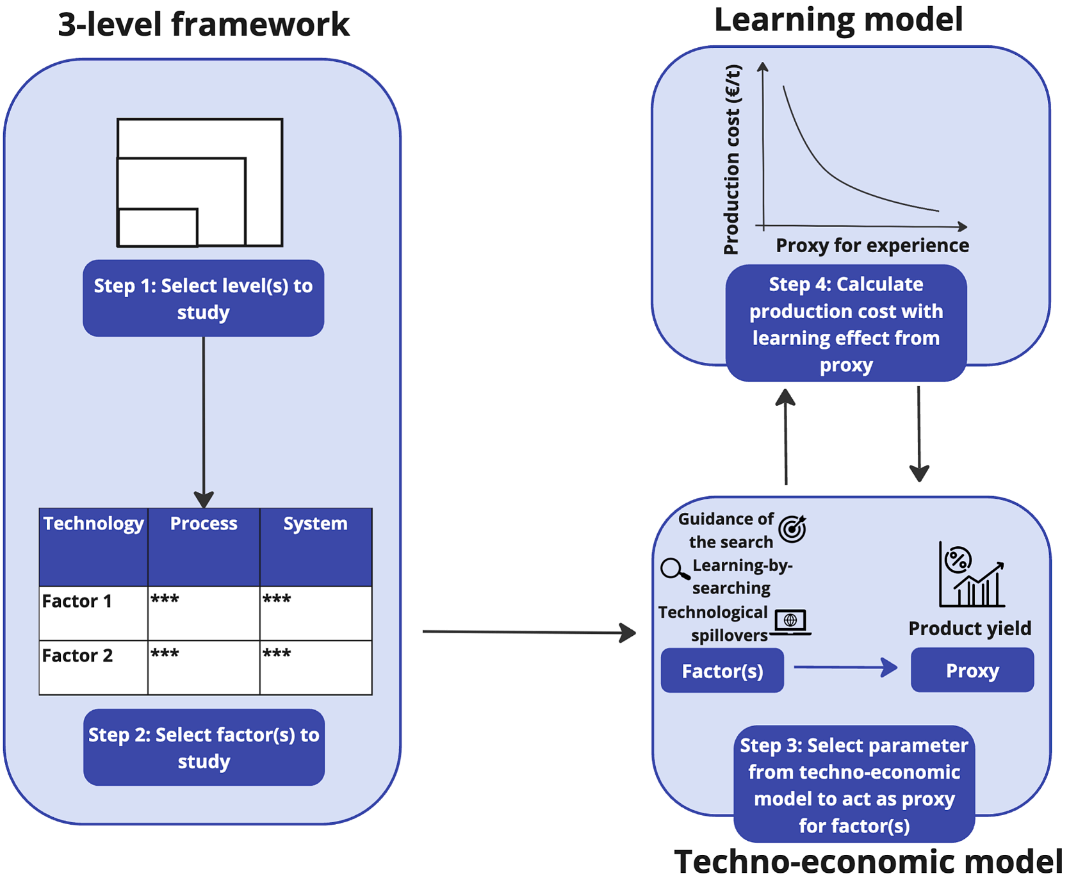


Fig. 4. Application of the 3-level framework to study technological learning for ethylene production technologies.

Xi is the cumulative production
Xo is the initial cumulative production
b is the learning parameter

$$LR = 1 - 2^{b} \tag{5}$$

Yield improvements cannot proceed indefinitely due to thermodynamic and kinetic limitations. A literature review was done to determine the highest yield that currently can be achieved for each technology. This value is used to limit the cost reductions at the technology level. The ethylene yields found in literature for each technology are shown in Fig. 2.

Learning at the process level

At the process level, the learning effect is investigated by assuming that thanks to learning-by-doing, the capital investment cost reduces by a fixed percentage with every doubling of the CIC (See Equation (5). Values lower than the typical 20 % LR are considered because of the scale and complexity of the processes [67]. After learning occurs, the capital investment of new plants would be lower. This directly reduces the levelized cost.

$$CAPEX_i = CAPEX_o * \left(\frac{Z_i}{Z_o}\right)^{b} \tag{6}$$

where:
$CAPEX_i$ is the capital investment cost after learning.
$CAPEX_o$ is the initial capital investment cost.
Zi is the cumulative installed capacity.
Zo is the initial cumulative installed capacity.
b is the learning parameter.

Learning at the system level

At the system level, we assume that the levelized cost reduces by a fixed percentage with every doubling of the CP. Values lower than the typical 20 % LR are considered because of the scale and complexity of the processes [67]. We identify how these cost reductions can be achieved, with insights from the sensitivity analysis and the cost reductions at the two other levels.

$$LCO_i = LCO_o * \left(\frac{X_i}{X_o}\right)^{b} \tag{7}$$

where:
LCO_i is the levelized cost after learning.
LCO_o is the initial levelized cost.
Xi is the cumulative production
Xo is the initial cumulative production
b is the learning parameter.

Results

Base case

Fig. 5 shows the levelized cost of ethylene in €$_{2019}$/tC_2H_4 for eight different technologies. For each one, we consider ethylene production with fossil, bio-based and synthetic feedstock. For ethanol dehydration, we do not consider fossil feedstock, but rather 1st generation biomass (shown in yellow). This is because currently the most common method to produce ethanol is through the fermentation of sugars or starches. For CO_2 electrolysis we consider a scale of 10 MW$_e$, while for the other technologies, we consider 1 MMTA.

Three different shades are shown in the boxplot. From top to bottom, the shades represent the contribution from variable OPEX (lightest shade), fixed OPEX (middle shade), and CAPEX (darkest shade). The technology with the highest CAPEX contribution is CO_2 electrolysis, where around 55 % of the production cost is attributed to the CAPEX. For MTO, the CAPEX has just a marginal contribution to the production cost, while for the other technologies, between 2 and 28 % is attributed to the CAPEX, depending on the feedstock used. For most of the

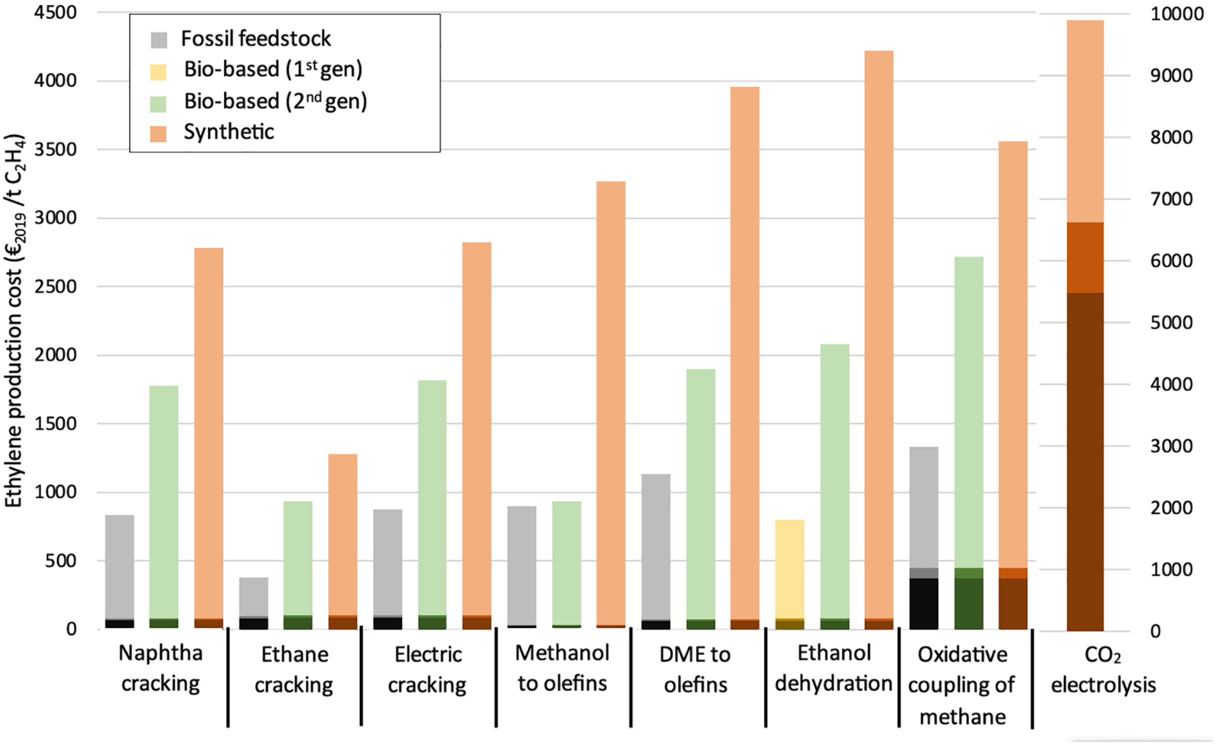


Fig. 5. Levelized cost of ethylene produced by eight different technologies, with different feedstock types. From top to bottom, the shades represent the share contribution from variable OPEX (lightest shade), fixed OPEX (middle shade), and CAPEX (darkest shade). For CO_2 electrolysis we consider a scale of 10 MW$_e$, while for the other technologies, we consider 1 MMTA. The performance and feedstock prices considered are found in the Supplementary Information.

technologies between 60–90 % of the production cost is attributed to the variable OPEX, more specifically, the feedstock cost. Just for CO_2 electrolysis the variable OPEX is around 33 % of the production cost, which corresponds mainly to electricity cost.

The cheapest ethylene is produced via fossil ethane cracking. The levelized cost is as low as 380€/t. Ethanol produced via 1st generation bio-ethylene dehydration has a levelized cost of 800€/t. The third cheapest option is fossil naphtha cracking, which has a levelized cost of 835€/t. The most expensive pathways are DMETO, ethanol dehydration, and CO_2 electrolysis fed with synthetic feedstock. The levelized costs amount to 3960€/t, 4220€/t, and 9900€/t, respectively. Bio-based ethylene is up to three times more expensive than the current average market price, while synthetic ethylene can be up to nine times more expensive.

Sensitivity analysis

Fig. 6 shows the effect of changing seven different parameters in the levelized cost of ethylene for electric cracking of synthetic naphtha. A literature review was done to determine the maximum and minimum values reported for bio-based and synthetic feedstock prices, as well as performance, and CAPEX per technology (See Supplementary Information). These values were used to perform a sensitivity analysis. We vary the feedstock price, performance, electricity price, fixed OPEX, CAPEX, discount rate, and plant lifetime, according to what is indicated in the figure.

For electric cracking, the feedstock price is by far the parameter with the highest impact on the levelized cost, followed by performance. Both are related to the variable cost. Even with the cheapest feedstock price reported in literature synthetic ethylene still costs twice as much as fossil ethylene. Enhancing technological performance can contribute to further reduce cost down to 1585€/t. However, achieving cost competitiveness ultimately requires policy interventions at the market level to drive down feedstock prices and create favorable market conditions for synthetic ethylene production. Capital costs and related parameters (fixed OPEX, discount rate, and lifetime) have a marginal contribution to the production cost, this might have to do with the fact that the cost calculations for this technology are done assuming a production of 1MMTA, therefore benefiting from economies of scale.

Sensitivity analyses for the other technologies can be found in the Supplementary Information. For ethanol dehydration, the most significant parameter affecting cost is the price of the feedstock, while for MTO, OCM, and DMETO, the primary factor influencing the levelized cost is the ethylene yield, followed by feedstock price. When producing ethylene via CO_2 electrolysis, the levelized cost is mostly impacted by CAPEX and electricity consumption.

Learning and cost reductions

Technology level

The starting point of each LC is the levelized cost calculated with the base case assumptions. For each technology nine different cost projections are shown for 2050, depending on the LR assumed and the scenario considered (See Appendix C). We model the cost reductions at the technology level, considering three different LRs: 1 %, 3 %, and 5 %. The maximum CP reached under each scenario is shown with vertical dotted lines. These values differ per technology, because of the assumed adoption levels (See Supplementary Information). The horizontal red dashed line marks the levelized cost at the highest ethylene yield found in literature, which limits the cost reductions at this level. The shaded area represents uncertainty ranges for the LR.

Fig. 7a shows the cost reductions at the technology level achieved by the projected CP in 2050 for electric cracking of synthetic naphtha, the initial production cost of ethylene is 2824€/t. Under the **'Joint supply'** scenario, the CP reaches 250Mt and the levelized cost reduces to 2620€/t (LR = 1 %), 2260€/t (LR = 3 %), and 2190/t (LR = 5 %). For the **'Phase out'** scenario the CP amounts to 1113 Mt, and the costs reach 2570€/t (LR = 1 %), and 2190€/t (LR = 3 % and LR = 5 %). In the '***One takes all***' scenario the CP is 2044 Mt. The levelized cost reduces to 2550€/t (LR = 1 %), and 2190€/t (LR = 3 % and LR = 5 %). This would be the maximum cost reductions that can be achieved at the technology level until 2050.

For MTO (See Fig. C2 in Appendix), the LC starts at 3260€/t. Considering an LR of 1 % and the **'One takes all'** scenario, the costs reduce to 3000€/t. With an LR of 3 % the levelized cost reaches 2680€/t, and with a LR of 5 %, the maximum cost reductions at the technology level amount to 2340€/t. Under the **'Phase out'** scenario, the costs reach 3086€/t (LR = 1 %), 2750€/t (LR = 3 %), and 2450€/t (LR = 5 %).

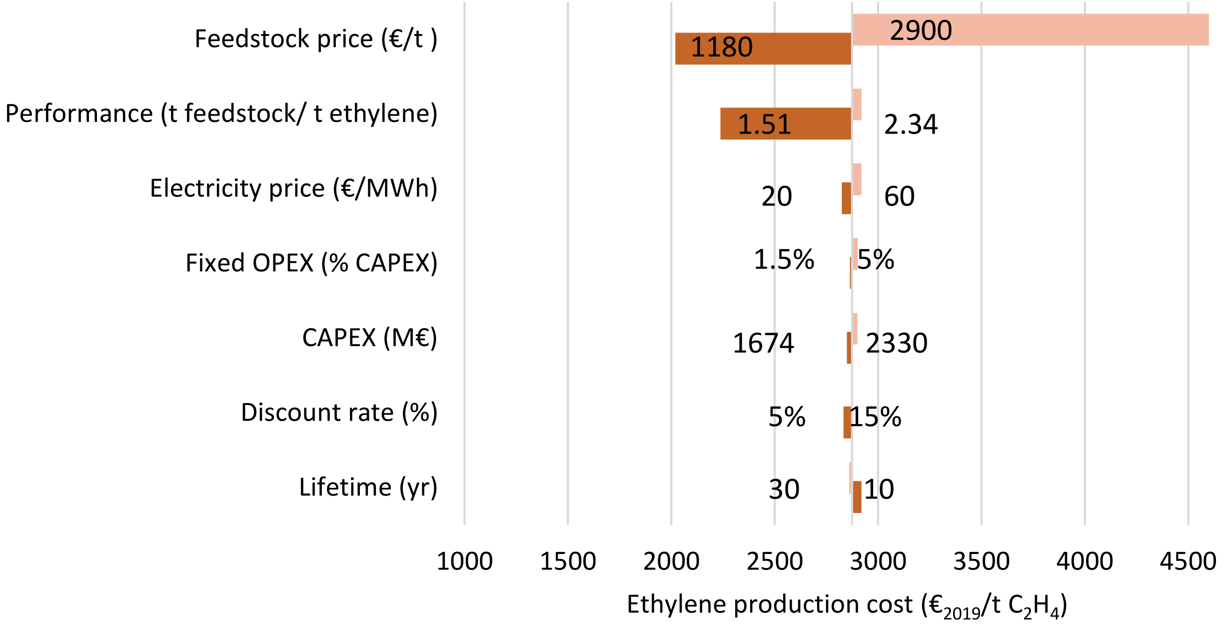
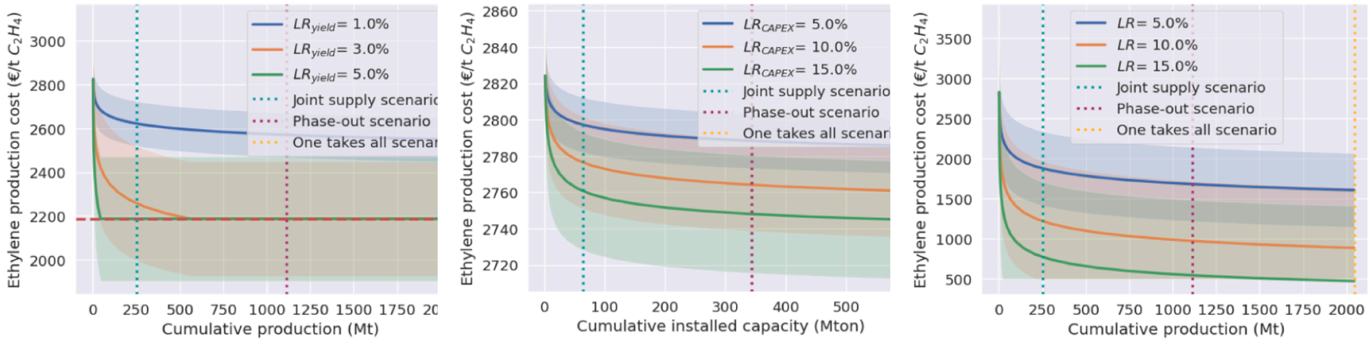


Fig. 6. Sensitivity analysis for electric cracking of synthetic naphtha. Seven parameters are varied to explore their effect on the current levelized cost of ethylene production. The average market price of fossil ethylene amounts to 1000€/t.



a) Projected cost reductions at the technology level.

b) Projected cost reductions at the process level.

c) Projected cost reductions at the system level.

Fig. 7. Projected cost reductions at the technology, process, and system level for electric cracking of synthetic naphtha under three scenarios. Cost reduction projections for the other five technologies can be found in the Appendix.

Finally, considering the **'Joint supply'** scenario the cost reductions reach 3100€/t (LR = 1 %), 2860€/t (LR = 3 %), and 2600€/t (LR = 5 %).

Fig. C3 (See Appendix) shows an LC for OCM at the technology level. The LC starts at a levelized cost of 3562€/t. Under the **'Joint supply'** scenario, the CP reaches 460Mt in 2050 and the cost reduces to 3350€/t (LR = 1 %), 2960€/t (LR = 3 %), and 2640€/t (LR = 5 %). For the **'Phase out'** scenario the CP amounts to 1762Mt, and the costs reach 3300€/t (LR = 1 %), and 2850€/t (LR = 3 %), and 2500 (LR = 5 %). In 2050, the costs reach 3260€/t (LR = 1 %), 2750€/t (LR = 3 %), and 2500€/t (LR = 5 %) under the '**One takes all'** scenario.

Fig. C4 (See Appendix) shows an LC at the technology level for the levelized cost of CO_2 electrolysis. The cost reduced from an initial value of 9900€/t to 9565€/t (LR = 1 %) in the **'One takes all'** scenario. With a LR equal or higher than 3 %, the maximum cost reductions at the technology level are reached, regardless of the scenario. The lowest cost achieved at this level is 9320€/t.

An LC for DME-to-olefins is shown in Fig. C5 (See Appendix). The initial production cost is 3960€/t. Under the '**One takes all**' scenario, the levelized cost in 2050 reaches 3690€/t (LR 1 %), 3200€/t (LR = 3 %), and 2780€/t (LR = 5 %). For the **'Phase out'** scenario, the CP amounts to 2450Mt, and the levelized cost reduces to 3720€/t (LR = 1 %), 3300€/t (LR = 3 %), and 2920€/t (LR = 5 %). Finally, in the **'Joint supply'** scenario the cost reduction is limited to 3770€/t (LR = 1 %), 3440€/t (LR = 3 %), and 3125€/t (LR = 5 %).

For ethanol dehydration of synthetic ethanol (See Fig. C6 in Appendix), the initial levelized cost of ethylene is 4220€/t. Under the **'Joint supply'** scenario, the CP reaches 222Mt and the levelized cost reduces to 4000€/t (LR = 1 %), 3630€/t (LR = 3 %), and 3277€/t (LR = 5 %). For the **'Phase out'** scenario the CP amounts to 782 Mt, and the costs reach 3940€/t (LR = 1 %), and 3440€/t (LR = 3 %), and 2990€/t (LR = 5 %). In the '***One takes all***' scenario the CP is 1452Mt, and the levelized cost reduces to 3900€/t (LR = 1 %), 3350€/t (LR = 3 %), and 2860 (LR = 5 %). These are the maximum cost reductions that can be achieved at the technology level until 2050.

In terms of the CP, relatively less experience is required for electric cracking and CO_2 electrolysis to reach the highest ethylene yield found in literature. Using the current average price of ethylene as a benchmark for cost competitiveness, none of the technologies would be able to reach competitive breakeven in 2050 if learning only occurs at the technology level. We used the most recent yield improvements reported in the literature for the current analysis. However, ongoing updates are required to ensure the model remains current.

Process level

The starting point of each LC is the levelized cost calculated with the base case assumptions. Nine different cost projections for 2050 are shown at the process level for six new ethylene production technologies fed with synthetic feedstock. (See Figure D in Appendix). In this case the proxy for experience is the CIC. The three different scenarios for the CIC are shown with vertical dotted lines. The shaded area represents uncertainty ranges for the LR.

The CAPEX of electric cracking reduces from an initial 1343 M€ to 840 M€ (LR = 5 %), 510 M€ (LR = 10 %), and 300 M€ (LR = 15 %) in 2050, considering the ***'One takes all'*** scenario. This results in a reduction of the levelized cost to 2786€/t (LR = 5 %), 2760€/t (LR = 10 %), and 2745€/t (LR = 15 %), respectively. Less optimistic projections are calculated following the ***'Joint supply'*** scenario, where levelized cost reduces to 2760-2800€/t, and the ***'Phase out'*** scenario, in which cost reduces to 2748-2788€/t (See Fig. 7b).

The levelized cost of MTO starts at 3260€/t, with a CAPEX of 760 M€. This value reduces to 680 M€ (LR = 5 %), 604 M€ (LR = 10 %), and 530 M€ (LR = 15 %) under the '***Joint supply***' scenario, and to 610 M€ (LR = 5 %), 480 M€ (LR = 10 %), and 370 M€ (LR = 15 %) under the ***'Phase out'*** scenario. Under the ***'One takes all'*** scenario the CAPEX reduces to 586 M€ (LR = 5 %), 441 M€ (LR = 10 %), and 326 M€ (LR = 15 %). The levelized cost reduces to 3256–3247 €/t (See Fig. D2 in Appendix).

The LC for OCM starts at a CAPEX of 3111 M€, amounting to a levelized cost of 3562€/t. Under the **'Joint supply'** scenario, the levelized cost reduces to 3440€/t (LR = 5 %), 3350€/t(LR = 10 %), and 3280€/t (LR = 15 %). For the ***'Phase out'*** scenario, the levelized cost reaches 3400€/t(LR = 5 %), 3294 €/t (LR = 10 %), and 3220(LR = 15 %). The maximum CAPEX reduction is achieved under the ***'One takes all'*** scenario, CAPEX reduces to 1833 M€ (LR = 5 %), 1050 M€(LR = 10 %), and 580 M€ (LR = 15 %). This results in a levelized cost in 2050 of 3376€/t (LR = 5 %), 3260€/t(LR = 10 %), and 3195€/t (LR = 15 %) (See Fig. D3 in Appendix).

For CO_2 electrolysis (See Fig. D4 in Appendix), the initial levelized cost of ethylene is 9900€/t, with a CAPEX of 47 M€ for a 10 MW_e electrolyzer. Under the **'Joint supply'** scenario, the levelized cost reduces to 8137€/t(LR = 5 %), 6780€/t(LR = 10 %), and 5760/t (LR = 15 %). For the **'Phase out'** scenario, the costs reach 7568€/t(LR = 5 %), 5990€/t (LR = 10 %), and 4950€/t (LR = 15 %). In the '***One takes all***' scenario, the levelized cost reduces to 7400€/t (LR = 5 %), and 5780€/t (LR = 10 %), and 4750€/t (LR = 15 %).

Under the ***'Joint supply'*** scenario, the levelized cost of synthetic ethylene produced via DMETO reduces form an initial 3956€/t to 3948€/t (LR = 5 %), 3940€/t (LR = 10 %), and 3930(LR = 15 %), in 2050. More optimistic projections are done following the ***'Phase-out'*** scenario, where CAPEX reduced to 675 M€- 410 M€ and the levelized cost reduces to 3940-3020€/t, and the ***'One takes all'*** scenario, where cost reduced to 3940€/t (LR = 5 %), 3925€/t (LR = 10 %), and 3914€/t (LR = 15 %) in 2050 (See Fig. D5 in Appendix).

For ethanol dehydration, the LC starts at a levelized cost of 4220€/t (see Fig. D6 in Appendix). This is reduced to 4195€/t (LR = 5 %), 4178 (LR = 10 %), and 4165 (LR 15 %), considering scenario **'One takes all'**. Less optimistic cost reduction is projected for scenario ***'Phase out'***, where the levelized cost reaches values between 4190 and 4168€/t. Even less cost reduction is achieved in the ***'Join supply'*** scenario, in which the maximum cost reduction reached are down to 4182€/t.

For most of the technologies, the cost reductions projected with the assumed LRs are within the CAPEX ranges found in literature (See Fig. 3). However, for DMETO, the projected CAPEX reductions are as low as 362 M€ while the lowest CAPEX reported in literature for this technology is 814 M€, and for OCM the projected CAPEX reductions amount to 582 M€, while the lowest value reported in literature is 1283 M€. Most of the data used comes from *ex-ante* techno-economic analyses, or models. Access to data of real and current engineering and building process plants is needed to further assess the feasibility of these projections.

Using the current average price of ethylene as a benchmark for cost competitiveness, none of the technologies are projected to achieve competitive costs by 2050 if only learning at the process level occurs. However, reductions in the CAPEX, might promote the deployment of these technologies. This is because investments are more likely to occur if the perceived risk is reduced through lower initial capital requirements.

System level

At the system level, we apply the LC equation to the levelized cost. We assume that for every doubling of the CP, the levelized cost reduces by a given percentage. This LC includes the effect of all the factors that could drive the cost reductions. Values lower than the typical 20 % LR are considered because of the scale and complexity of the processes. The shaded area represents uncertainty ranges for the LR. The three different scenarios are shown with vertical dotted lines.

Fig. 7c shows the projected cost reductions at the system level for electric cracking of synthetic naphtha. Under the '***One takes all***' scenario, the levelized cost of ethylene produced by electric cracking can be as low as 480€/t in 2050, if we assume an LR of 15 %. For this technology, the main determinants of the levelized cost are the feedstock price and the yield improvements (See Fig. 6). From the technology level analysis, we know that the cost can reduce to 2190€/t in 2050 as a result of yield improvements. Therefore, the rest of the cost reductions would have to come from the feedstock price. The price of synthetic naphtha would have to be around five times cheaper than the current price. However, if no improvements are achieved at the technology level, all cost reductions would have to come from the feedstock price. Even a lower price of 230€/t (seven times cheaper than current price) would be needed to reach the projected levelized cost of ethylene.

The lowest projected cost for MTO fed with synthetic MeOH is achieved with an LR of 15 % in the '***One takes all***' scenario (See Fig. E2 in Appendix). The projected levelized cost in 2050 amounts to 1030€/t. The sensitivity analysis (See Supplementary Information) shows that the main determinants of the levelized cost are the feedstock price and the performance improvements. From the technology level analysis, we know that the cost can reduce to 2340€/t. To reach the projected cost in 2050, the price of synthetic MeOH needs to be approximately 1220€/t. If, however, no improvements are achieved at the technology level, the price of synthetic MeOH would have to be between 450 and 475€/t.

The lowest projected cost at the system level for OCM fed with synthetic methane is 529€/t (LR = 15 %) in the '***One takes all***' scenario (See Fig. E3 in Appendix). The determinants of the levelized cost are yield improvements, feedstock price, and CAPEX (See Supplementary Information). The projected cost reductions at the technology level in 2050 can reach 2500€/t. At the process level, the CAPEX can decrease to 580 M€ in 2050 (LR = 15 %) in the '***One takes all***' scenario. The levelized cost of ethylene in 2050 considering learning at the technology and process levels amounts to 2150€/t. The rest of the cost reductions should come from the feedstock price. However, even with a feedstock price as low as 2€/GJ of synthetic natural gas, the levelized cost does not reach 529€/t. This low cost might, however, be achieved if fossil or bio-based feedstock are used instead, or with further improvements at the technology and process levels.

The projected cost reduction under the '***One takes all***' scenario for CO_2 electrolysis at the system level reaches 1662€/t with a LR = 15 % (See Fig. E4 in Appendix). The determinants of the levelized cost are electricity price, CAPEX, and improvements of the faradic efficiency (See sensitivity analysis in Supplementary Information). Improvements at the technology level result in a levelized cost of 9320€/t. Under the '***One takes all***' scenario, and an LR of 15 % at the process level, CAPEX reduces to 10 M€ in 2050, which further reduces the levelized cost to 4170€/t. The rest of the cost reductions should come from the electricity price. However, with electricity prices as low as 5€/MWh, the levelized cost does not reach the projected cost reductions at the system level. Further improvements at the technology and process levels are required to reach the projected cost of 1660€/t.

Cost reductions at the system level for DMETO under the '***One takes all***' scenario reaches 1250€/t (LR = 15 %) in 2050 (See Fig. E5 in Appendix). The sensitivity analysis (See Supplementary Information) shows that the main determinants of the levelized cost are the feedstock price and the performance improvements. From the technology level analysis, we know that the cost can reduce to 2780€/t. The rest of the cost reductions would need to come from the feedstock price. The price of synthetic DME needs to be approximately 925€/t to achieve the projected cost reductions in 2050. If, however, no improvements are achieved at the technology level, the price of synthetic DME would have to be as low as 575€/t.

The lowest cost projections for the levelized cost of ethylene produced via synthetic ethanol dehydration are achieved under the '***One takes all***' scenario, and an LR of 15 % (See Fig. E6 in Appendix). Under these assumptions the levelized cost can reach a value of 1195€/t. Given the results of the sensitivity analysis, the main determinants of the levelized cost are the feedstock price and performance improvements. From the analysis at the technology level, we can conclude that the levelized cost can be reduced down to 2850€/t, if the yield is improved. The rest of the cost reductions would have to come from the feedstock cost. Synthetic ethanol should have a price of 1100€/t to achieve the projected cost reductions in 2050. However, if no improvements are done at the technology level, the price of synthetic ethanol should be lower than 675€/t to reach a value of 1195€/t.

Discussion

Considering the relevance, data availability, and technology maturity of options to decarbonize and defossilize ethylene production, six new technologies were selected for this analysis: electric cracking, ethanol dehydration, OCM, DMETO, MTO, and CO_2 electrolysis. A techno-economic model was developed with data from literature to calculate the levelized cost of fossil, bio-based, and synthetic ethylene. We found out that bio-based ethylene is up to three times more expensive than the current average market price, while synthetic ethylene can be up to nine times more expensive. For electric cracking and ethanol dehydration, the most significant parameter affecting cost is the price of the feedstock. Additionally, we determine that for MTO, OCM, and DME-to-olefins, the primary factor influencing the levelized cost is the ethylene yield. When producing ethylene via CO_2 electrolysis, the levelized cost is mostly impacted by CAPEX and electricity consumption.

Our three-level approach allows to, jointly or individually, study cost reductions at the technology, process or system level. For each level, nine different cost projections are shown for 2050, depending on the LR assumed and the deployment scenario considered. Using the current average price of ethylene as a benchmark for cost competitiveness, none of the technologies would be able to reach competitive cost in 2050 if learning just occurs at the technology level. Learning at this level is limited by the performance improvements reported in literature. Under the ‘Joint supply’ scenario and LR of 5 %, only CO_2 electrolysis and electric cracking reach their maximum highest ethylene yield by 2050. This happens for the rest of the technologies only under the ‘One takes all’ scenario, which assumes that all the ethylene demand is supplied by just one technology. Due to the minor contribution of CAPEX to the levelized cost for most of the technologies, learning at the process level has marginal effect on the overall cost reductions. Just, for CO_2 electrolysis learning at the process levels has a considerable effect on the cost reductions. CAPEX reductions might promote the deployment of these technologies, because investments are more likely to occur if the perceived risk is reduced through lower initial capital requirements. For most of the technologies the projected CAPEX in 2050, match with the lower bounds found in literature. At the system level, no one technology reaches cost competitiveness by 2050, considering the ‘Joint supply’ scenario, and a LR of 5 %. Under the most optimistic assumptions (‘One takes all’ scenario LR = 15 %), electric cracking of synthetic naphtha, synthetic MTO, and OCM fed with synthetic methane have the potential to be competitive by 2050.

Fig. 8 shows the average, most optimistic and least optimistic projected cost reductions. The most optimistic projected cost of ethylene produced via electric cracking of synthetic naphtha is 480€/t. Without yield improvements, feedstock costs need to decrease significantly, even down to 230€/t, to meet this projection. The cost of ethylene from synthetic MTO could reach 1030€/t by 2050. Achieving this cost requires synthetic methanol prices around 1220€/t. However, without learning at the technology level, the feedstock price would need to reduce to 450-475€/t. The cost of ethylene from synthetic DMETO drops to 1250€/t under the most optimistic assumptions. Synthetic DME needs to be around 1430€/t to achieve this, or even lower (550€/t) if no learning at the technology level occurs. The lowest projected cost of ethylene from synthetic ethanol dehydration is 1195€/t, which can be achieved with a synthetic ethanol price of 1100€/t. However, in the absence of yield improvements, the synthetic ethanol price should be lower than 675€/t. The projected cost of ethylene produced via OCM fed with synthetic methane is 529€/t. With learning at the technology and process levels, the production cost can go down to 2150€/t. The rest of the cost reductions should come from the feedstock price. However, even with low-cost synthetic methane (2€/GJ), the projected 529€/t are not reached. Further technological, and process improvements are needed to meet this target. The most optimistic projected cost of ethylene from CO_2 electrolysis reaches 1660€/t in 2050. However, even with an electricity costs of 5€/MWh, as well as projected learning at the technology (improving FE) and process levels (CAPEX reduction), it is not possible to meet this goal. There is high uncertainty regarding the future prices of bio-based and synthetic feedstock. A more detailed analysis of current and projected feedstock prices is necessary to mitigate the uncertainty associated with the cost projections.

For industrial stakeholders, we suggest collaborating with researchers to validate the modeling results and reduce uncertainty of the projected costs, as well as fostering knowledge and data exchange. For electric cracking, DMETO, and CO_2 electrolysis, we suggest testing the reported technological performance on pilot plants, which would validate the data found in literature, and further advance the development of these technologies. For MTO and ethylene dehydration, we suggest a deeper analysis of real project cost data which could result in the identification of other potential cost reductions. Also, an LR can be obtained by fitting an LC to historical cost data from existing plants. Data collection efforts can be conducted through organizations such as IRENA and IEA, utilizing questionnaires and supplementary desk research to ensure access to comprehensive, up-to-date datasets while upholding confidentiality.

For policy makers, we suggest considering tailored strategies to drive the cost reductions of each technology. For electric cracking, and MTO we propose policies that address the high feedstock prices. For example, feed-in tariffs can be used to ensure investment security and a predictable cost of sustainable ethylene. Also, CO_2 tax can be implemented to decrease the competitive advantage of fossil ethylene. For CO_2

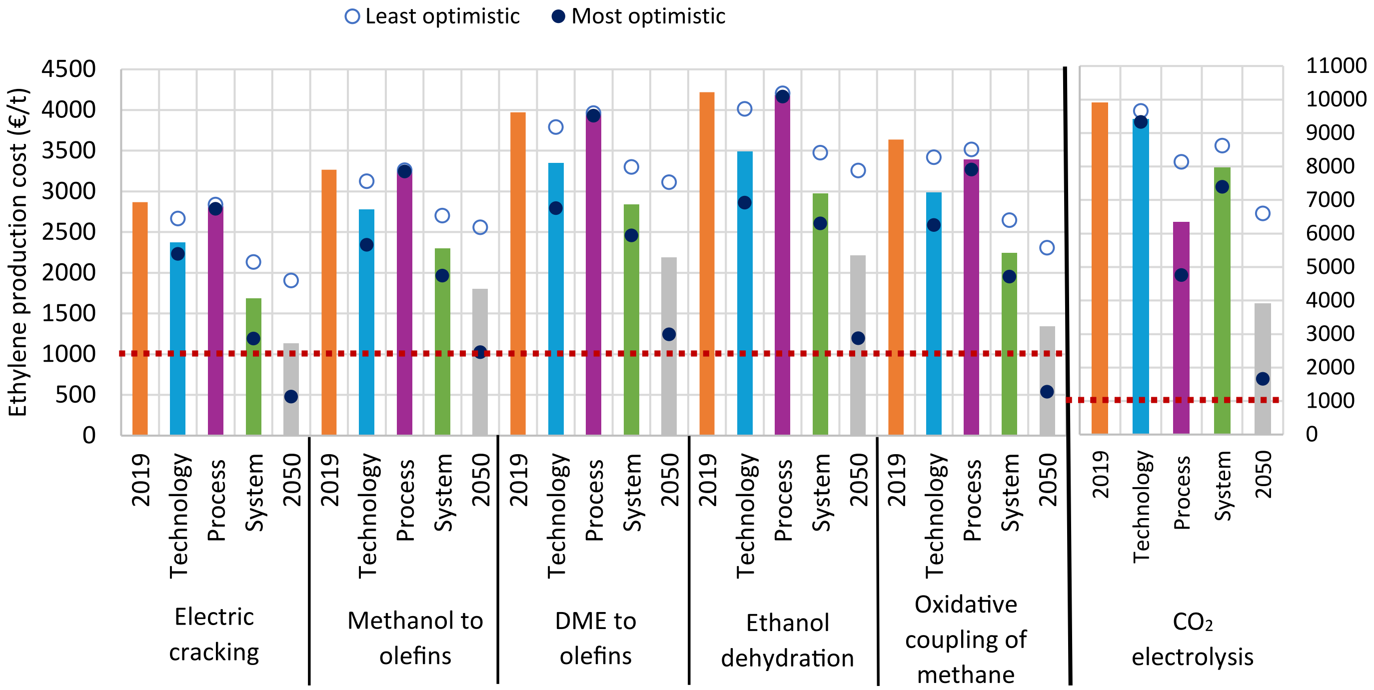


Fig. 8. Summary of the projected cost of ethylene produced by six different technologies fed with synthetic feedstock. The bars show the average values, the dark circles show the most optimistic assumptions (‘One takes all’ scenario & LR = 15 %), and the light circles the least optimistic assumptions (‘Joint supply’ scenario & LR ≤ 5 %). The orange bar indicates the current production cost. The bars in blue, pink and green correspond to the cost reductions from the technology level, process level, and system level, respectively. The grey bar shows the average projected ethylene costs in 2050. The current average market price of fossil ethylene amounts to 1000€/t, indicated with a horizontal dotted red line.

electrolysis and OCM, we recommend focusing on initiatives that promote R&D, technology spillovers, and guidance of the search to achieve higher technological performance and to develop demonstration test. This can be done by means of loans and grants for R&D support. Also, given the capital-intensive nature of these technologies we propose policies that help mitigate perceived investment risks. For example, fiscal incentives such as tax reductions, subsidies or rebates. For ethanol dehydration and DME-to-olefins, we suggest market-pull policies that encourage widespread adoption and accelerate market deployment. This can be achieved by mandates or obligations that drives market demand and encourages large-scale investments.

We recommend that researchers prioritize addressing existing data gaps. For electric cracking and CO_2 electrolysis we suggest performing a detailed chemical process design, since it was challenging to gather clear mass and energy balance data from process design reports and modeling literature for these technologies. We also suggest performing detailed techno-economic analyses, because it was difficult to obtain cost data from literature which had a detailed break-down of all the equipment cost, as well as a clear report of the cost calculations. For OCM, we suggest testing the membrane reactor performance on a lab-scale configuration, to validate modeling results.

The present work is an initial step towards providing quantitative insights on how to accelerate the development and deployment of low-carbon industrial technologies. Further research may focus on improving the methodology applied in the current work, by accounting for the interactions between learning at different levels. For example, efficiency improvements can result in a higher or lower CAPEX or might lead to a quicker payback period. Lower CAPEX would also have an effect in system level factors such as financial conditions, since lower investment costs would lead to lower financing costs. Additionally, the scope of the analysis could be broadened to model cost reductions in the upstream processes, or to include other low TRL ethylene production technologies, for example: microwave or shockwave heating steam crackers, plasma catalysis, or bio-catalysis. We recommend reevaluating the appropriateness of applying the LC equation to the levelized cost (cost reductions at the system level). This approach may lead to overly optimistic projections of cost reductions and may introduce substantial uncertainties. Research and development break-throughs could result in even higher performance improvements, which would affect the results presented in this work. Therefore, we suggest remaking this analysis if reports on new performance improvements are published. Synergies between the upstream and downstream, which benefit the cost competitiveness, could be included in the analysis. In follow-up work we recommend collaboration is sought with industrial stakeholders to obtain data from real projects, which could reduce the uncertainty of the cost projections presented in the present work. We also suggest the application of the three-level framework together with data-driven models or machine learning approaches to further enhance the robustness of the projected cost reductions.

Conclusions

Ethylene, one of the main petrochemicals, is still heavily dependent on fossil fuels, both as fuel and feedstock. There are various new technologies that could be used to decarbonize and defossilize ethylene production. However, these new technologies are not yet in state to be cost competitive with the established conventional processes.

The goal of this work was to determine under which technological learning and market deployment conditions renewable ethylene production technologies can become cost competitive by 2050. To reach this goal, we have applied a five-step methodology. Considering the relevance, data availability, and technology maturity of options to decarbonize and defossilize ethylene production, we selected six new technologies for this analysis: electric cracking, ethanol dehydration, OCM, DMETO, MTO, and CO_2 electrolysis. We have gathered performance and techno-economic data, and we have developed a techno-economic model to determine the current production cost of ethylene for each technology. We determined three different scenarios to calculate how much ethylene is supplied by each technology by 2050, and we projected cost reductions for each technology. We applied a three-level framework (with technology, process, and system as dimensions) which allowed us to, jointly or individually, study cost reductions at each level. Technology-level cost reductions were limited by the highest ethylene yield found in literature. Process-level learning showed to have a marginal impact on cost reductions for most technologies, except CO_2 electrolysis, where CAPEX reductions played a more significant role. The results at the system level revealed the high dependency on feedstock prices, which are currently subject to substantial uncertainty.

The present work gives guidelines on how to further improve technologies to produce ethylene via sustainable routes, as well as targets to increase the feasibility of achieving the projected cost reductions. Achieving cost-competitive, renewable ethylene production requires collaboration between researchers, industrial stakeholders, and policymakers. Cooperation should focus on promoting data availability and knowledge exchange, validating modeling results, achieving higher technological performance, developing small-scale demonstration plants, reducing feedstock prices, and encouraging widespread adoption of new technologies. The insights gained in the present work provide a foundation for guiding the transition toward sustainable ethylene production.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve readability and language of the work. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Daniela Anahi Toribio Ramirez: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Remko J. Detz:** Writing – review & editing, Supervision, Methodology, Conceptualization. **André Faaij:** Supervision. **Bob van der Zwaan:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

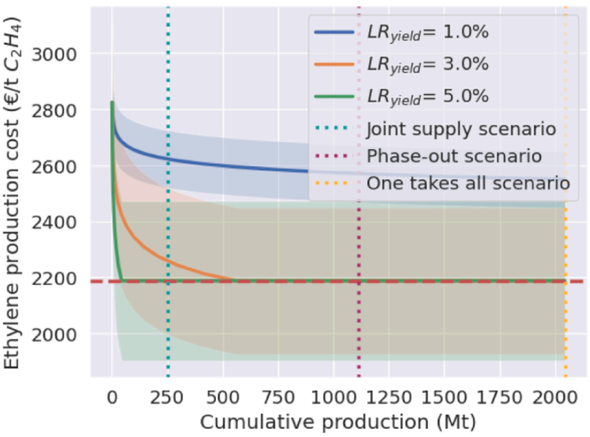
Appendix 1

Table A1
Summary statistics of the yields reported in literature, corresponding to data in Fig. 2.

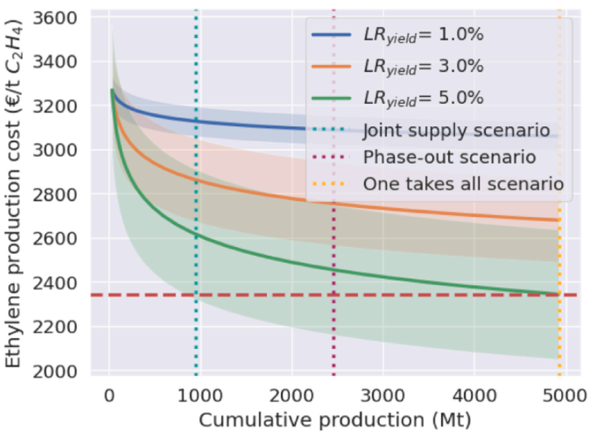
Technology	Mean (%)	Standard deviation (%)	Min/Max (%)	Source
Naphtha cracking	33	5.6	29/37	[9,15]
Ethane cracking	80	4	77/85	[9,15]
Electric cracking	40	4	34/46	[17,60]
Methanol-to-olefins	44	20	20/88	[43–46]
DME-to-olefins	36	16	13/63	[36,37,44]
Ethanol dehydration	88	19	13/99	[9,24,25,27]
Oxidative coupling of methane	33	14	15/63	[9,33,34]
CO_2 electrolysis (FE)	51	15	29/81	[54–57]

Table B1
Summary statistics of CAPEX values reported in literature, corresponding to data in Fig. 3.

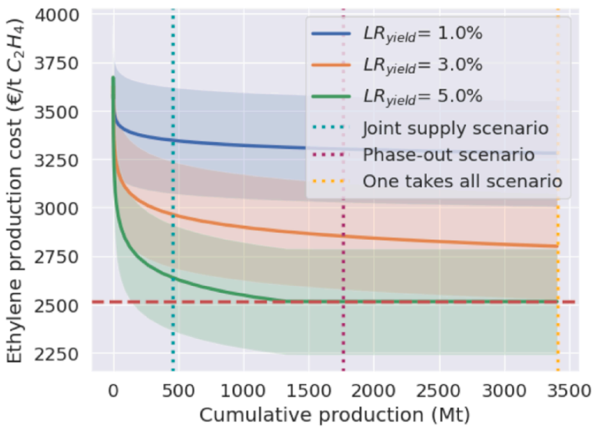
Technology	**Mean (M€$_{2019}$)**	**Standard deviation (M€$_{2019}$)**	**Min/Max (M€$_{2019}$)**	**Source**
Naptha cracking	1091	361	634/ 1505	[1,35,47,61]
Ethane cracking	1037	180	910/1164	[61]
Electric cracking	1343	1187	26/ 2330	[21,60]
Methanol-to-olefins	768	400	312/ 1805	[1,43,47,60]
DME-to-olefins	850	38	814/ 889	[38,39]
Ethanol dehydration	544	671	25/ 1835	[1,26,28,29,38,39]
Oxidative coupling of methane	3112	1068	1283/4292	[33,35]
CO_2 electrolysis (10 MW_e)	104	98	4.8/ 204	[54,56–58]



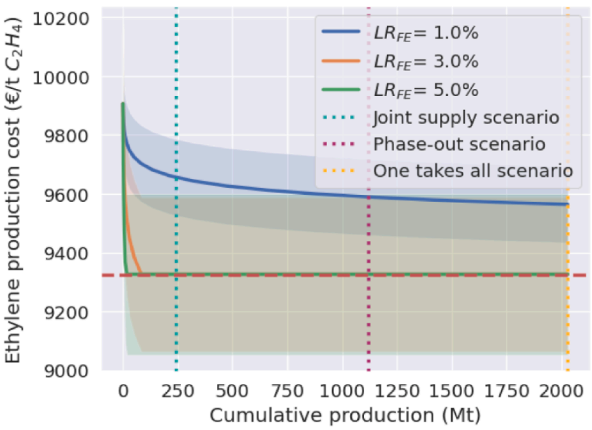
1. Projected cost reductions at the technology level for electric cracking under three different scenarios.



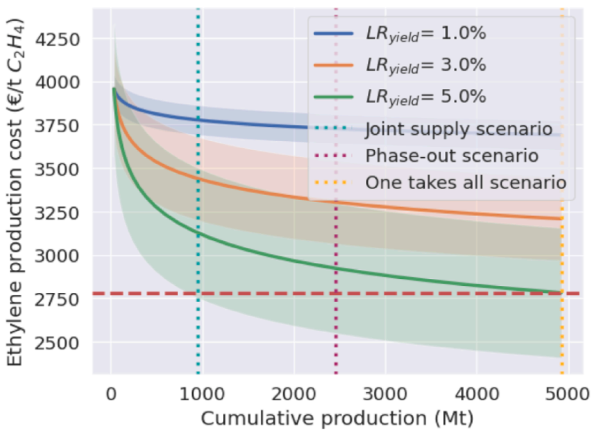
2. Projected cost reductions at the technology level for MeOH-to-olefins under three different scenarios.



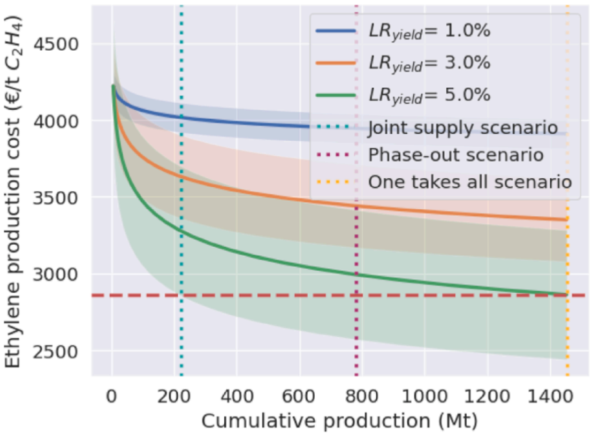
3. Projected cost reductions at the technology level for OCM under three different scenarios.



4. Projected cost reduction at the technology level for CO_2 electrolysis under three different scenarios.

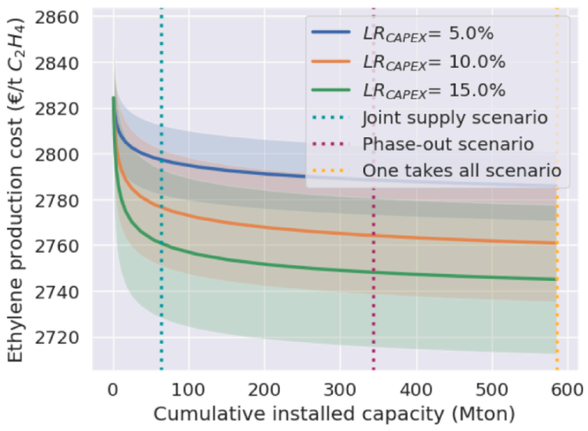


5. Projected cost reductions at the technology level for DME-to-olefins under three different scenarios.

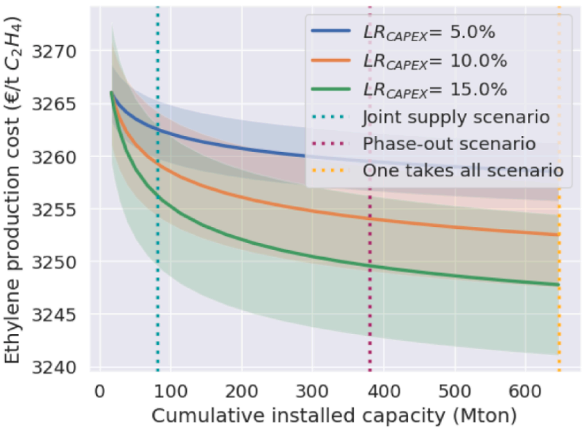


6. Projected cost reductions at the technology level for ethanol dehydration under three different scenarios.

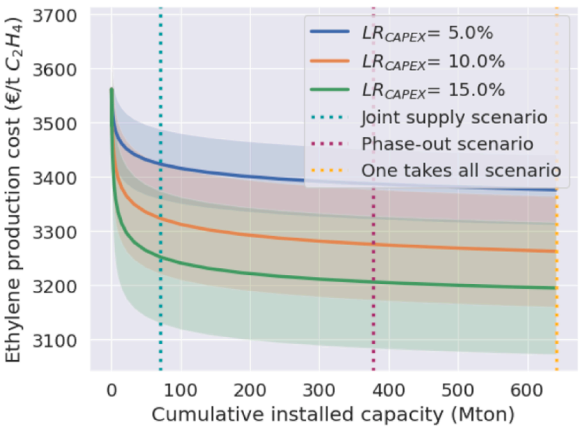
Fig. C. Projected cost reductions at the technology level under three different scenarios.



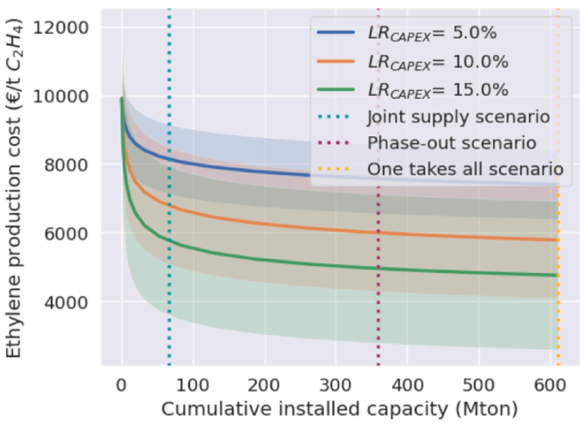
1. Projected cost reductions at the process level for electric cracking under three different scenarios.



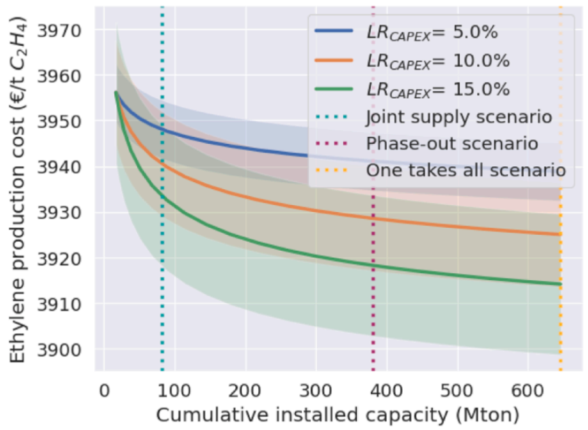
2. Projected cost reductions at the process level for MeOH-to-olefins under three different scenarios.



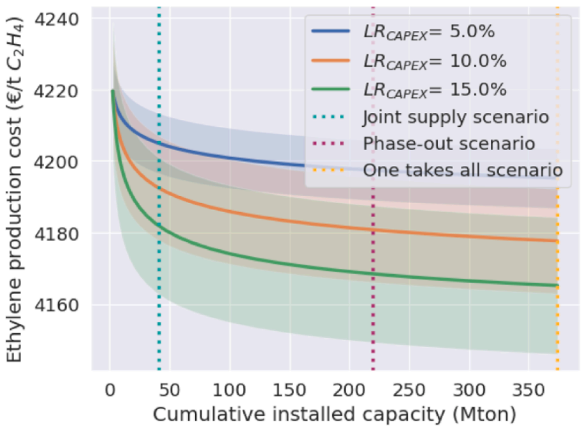
3. Projected cost reductions at the process level for OCM under three different scenarios.



4. Projected cost reduction at the process level for CO_2 electrolysis under three different scenarios.

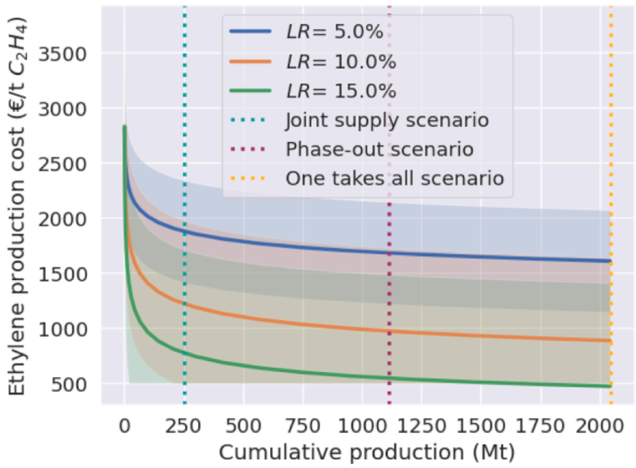


5. Projected cost reductions at the process level for DME-to-olefins under three different scenarios.

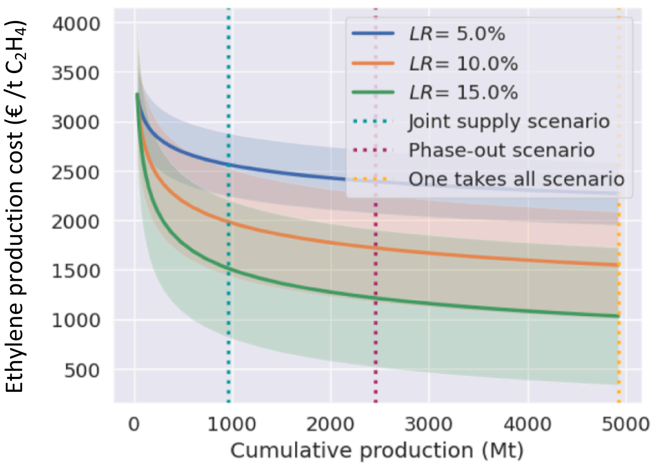


6. Projected cost reductions at the process level for ethanol dehydration under three different scenarios.

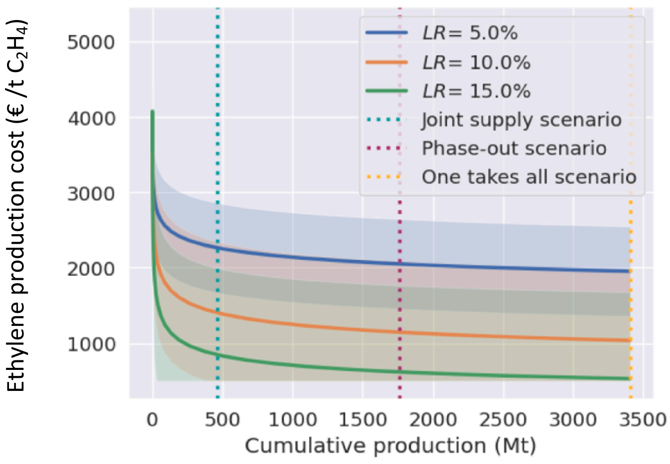
Fig. D. Projected cost reductions at the process level under three different scenarios.



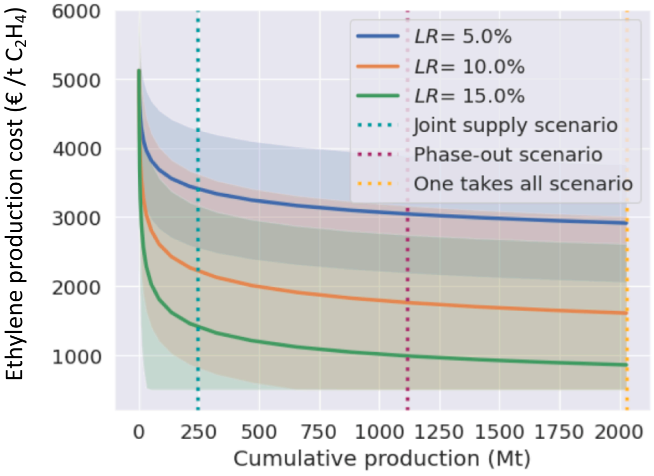
1. Projected cost reductions for electric cracking at the system level under three different scenarios.



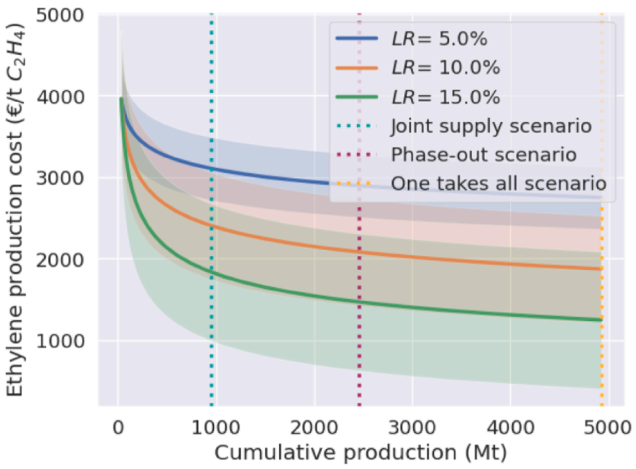
2. Projected cost reductions for MeOH-to-olefins at the system level under three different scenarios.



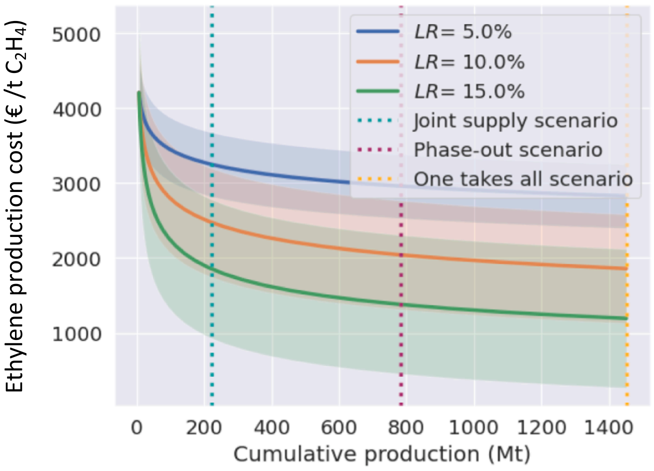
3. Projected cost reductions for OCM at the system level under three scenarios.



4. Projected cost reduction at the system for CO_2 electrolysis under three different scenarios



5. Projected cost reductions for DME-to-olefins at the system level under three different scenarios.



6. Projected cost reductions at the system level for ethanol dehydration under three different scenarios.

Fig. E. Projected cost reductions at the system level under three different scenarios.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2025.104306.

Data availability

Data will be made available on request.

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