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Review article

The costs of future energy technologies: A comprehensive review of power-to-X processes

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ABSTRACT

In this review, the techno-economic data for various emerging Power-to-X (PtX) technologies is summarized and discussed, with recommendations for appropriate values presented. These recommendations can serve as a reference in, e.g., energy system modeling, in which such data is desperately needed in order to define these novel processes and assess their impact on the energy system of the future. To this end, over 300 publications concerning PtX processes for gases (methane and syngas), fuels (methanol and synfuels) and chemicals (ethylene and formic acid) were evaluated in a structured literature search with respect to their financial key performance indicators (KPIs) such as capital expenditures (CAPEX) and operational expenditures (OPEX); process-specific KPIs such as efficiency, lifetime, and operating conditions; and their technology readiness levels (TRLs). The review finds that for all of the investigated technologies, significant cost reductions can be anticipated until 2050 due to scaling and learning effects. The magnitude of the cost reduction differs with each technology and is often connected to its degree of technological maturity. The prevalent technological immaturity of most processes also means that they are not yet cost-competitive with conventional fossil production technologies. Furthermore, data availability varies strongly between the assessed technologies and can influence the quality of the projections.

1. Introduction

In recent times, there has been increasing momentum in actions and plans aimed at mitigating the negative impacts of the climate crisis. Many countries have been implementing strategies geared towards developing low CO_2-emitting economies, which typically involve measures such as expanding the production capacity of renewable energy systems or increasing the share of battery electric vehicles in the transport sector, amongst others [1–3]. However, despite the positive effects that these measures can have in reducing carbon emissions, they also pose new challenges. For instance, the intermittency of renewable energy systems can threaten the security of supply in extreme scenarios [1,4–8]. In addition, there are several other sectors in which electrification is difficult and where hard-to-abate emissions persist, such as the chemical industry.

PtX processes refer to a group of technologies that can potentially transform these hard-to-abate sectors by converting renewable electricity into value-added products such as hydrogen, methane, ethylene, and many more, and thereby reduce sectoral carbon emissions. The definition of PtX used in this review draws upon the paper of Berger et al. (2020) and encompasses novel processes that use renewably-generated electricity to produce value-added products directly or indirectly [9]. However, indirect production is restricted to the second process level, such that processes requiring three or more process steps from power to product (e.g., ethylene production via MTO) [10] are excluded, as per the suggestions of Berger et al. (2020) [9].

The products resulting from PtX processes can be readily used in a variety of industrial processes and can substitute carbon-intensive conventional processes. Thereby, carbon emissions can be avoided or reduced, enabling industrial companies to reach their climate targets

Abbreviations: CAMERE, Carbon Dioxide Hydrogenation Process for Methanol Production via RWGS reaction; CAPEX, Capital Expenditure; CCU, Carbon Capture and Utilization; ECO_2RR, Electrochemical CO_2-Reduction Reaction; FT, Fischer-Tropsch; KPI, Key Performance Indicator; LHV, Lower Heating Value; MTG, Methanol-to-Gasoline; MTO, Methanol-to-Olefin; OCM, Oxidative Coupling of Methane; OPEX, Operational Expenditure; PEM, Proton Exchange Membrane; POX, Partial Oxidation; PtX, Power-to-X; RWGS, Reverse Water-Gas-Shift; SMR, Steam-Methane Reforming; SNG, Synthetic Natural Gas; SOEC, Solid Oxide Electrolyzer; TRL, Technology Readiness Level.

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[9]. Moreover, they can be used to store excess electricity, avoiding situations in which demand exceeds supply and can therefore add to the resilience and flexibility of the energy system [9,11]. Especially with respect to long-term storage, PtX processes offer the unique advantage of being able to store large capacities of electricity over long time periods, something that other storage systems fail to do [12]. However, despite the increasing popularity of PtX technologies amongst industry actors and policymakers, many such technologies are still not technologically mature or cost-competitive compared to conventional processes [13,14].

The technological immaturity of many PtX technologies makes it challenging to find consistent information in the literature regarding their maturity levels and underlying techno-economic parameters. This issue introduces a high level of uncertainty into predictions as a result of the variance of the values. Additionally, although research interest has intensified enormously over the past ten years (see figures A.1–A.6), the diversity of PtX technologies means that there are few reports that provide a structured overview that include many technologies instead of focusing on just one. Moreover, to the best of the authors knowledge, no publications addressing these issues exist that contain data collected within the last five years [13]. For rapidly evolving technologies such as PtX, techno-economic parameters are equally rapidly outdated, making it difficult to base projections on such values.

This review aims to fill this gap by providing a far-reaching overview of PtX technologies and their relevant techno-economic parameters. It focuses specifically on CO_2-consuming technologies, given the need for carbon capture and utilization (CCU) in future greenhouse gas neutral energy systems and carbon neutrality [15], as well as the inevitability of mitigating the most prominent greenhouse gas – CO_2 – to achieve climate targets [16]. For the purpose of this review, technologies producing methane and syngas (Power-to-Gas), methanol and synthetic fuels (Power-to-Liquid), and ethylene and formic acid (Power--to-Chemicals) were investigated. The main body of this review analyzes techno-economic information regarding the technologies. An overview of the process details and information about existing demonstration projects is presented in detail in the supplementary information section. This review also aims to support energy system modelers in the integration of PtX processes in the energy system by providing all of the necessary modeling parameters for the relevant technologies.

2. Methodology

A structured literature research approach was utilized to obtain a far-reaching overview of the relevant literature on each PtX product individually. The literature review followed the PRISMA guidelines flow chart for systematic literature reviews [17]. The SCOPUS database was selected for the literature search. A search string for each product was then developed and iteratively tested with a selection of suitable papers to ensure that it yielded relevant results without omitting important papers. The search string consisted of one part describing the product (e.g., methane), one part describing the general process (e.g., Power-to-Gas), and one part describing the techno-economic aspects (e.g., economic assessment). For all PtX products analyzed, this yielded n = 1359 publications. Then, articles were selected based on their title, including publications with ambiguous titles (n = 441). Subsequently, the abstract of each article was analyzed to exclude those that were not relevant to the review (n = 288). After this, the accessibility of the papers was verified (n = 273). The full text of each article was skimmed through to determine whether it contained purely techno-economic parameters of interest or whether there was additional information relevant to the review paper. Furthermore, by skimming through the article, its relevancy to the research topic was confirmed. Articles containing techno-economic parameters were analyzed and the relevant data extracted and stored in a database. In addition to the structured approach, ‘snowballing’ was used to retrieve additional relevant publications through references (n = 315). A list of the procedures for every product individually can be found in the appendix.

To derive a cost projection for the technologies in future years, an exponential fit was applied to the dataset of each technology and the values at the respective support years (2020, 2030, 2040 and 2050) were used in the cost recommendations. Given the limited availability for years other than the support years, no specific literature-based recommendations are provided for the intermediate years. Instead, modelers are advised to interpolate between the available years or directly employ the literature values if accessible. Cost data is always given in $€_{2022}$ and values which refer to a different year or a different currency were converted accordingly. If a cost year was explicitly stated in the publication, this year was chosen to account for inflation, otherwise the year prior to the publication year was assumed as the cost year. Cost ranges were separated in distinct data points with the lower value of the range corresponding to a best-case scenario, the mean value of the range to a base-case scenario and the upper bound of the range to a worst-case value. Determining the scope of elements included in the investment costs has been identified as a serious challenge in literature [18]. Herein, cost data always refers to the core reactor or core electrolyzer, depending on the technology, unless otherwise stated. Costs are given with respect to either input or output capacity depending on the process. This is specified for each technology individually in the respective chapter. For data which did not conform the standardized capacity – e.g. because it referred to input instead of output – it was adapted using the interpolated efficiency values calculated from the analysis of the technology’s efficiency and considering an interpolated mean efficiency for hydrogen electrolyzers. Efficiencies within this work always refer to the ratio between the energy of the reactants – either with respect to electricity input or with respect to the lower heating value (LHV) - and the LHV of the products. Values which did not conform this standard were converted – e.g., from HHV to LHV. Literature values for the efficiency which exceeded the thermodynamic limit, mostly due to erroneous extrapolation of values for later years in the publications, were omitted in the determination of adequate efficiency values for the support years. However, for completeness all efficiency data can be found in the supplementary data. For further parameters, such as technical lifetime and operational expenditures (OPEX), mean values were determined and used in the recommendations.

3. Power-to-methane

Power-to-Gas processes, such as Power-to-Hydrogen or Power-to-Methane, represent some of the only options for seasonal electricity storage at the necessary capacities for a country that relies on renewable energy technologies [19]. To this end, methane carries peculiar advantages over hydrogen, such as its capability of using existing natural gas infrastructure, its approximately four-fold higher energy density, its lower storage cost, and higher safety [18,20,21], although disadvantages like methane leakage and its higher price compared to conventional natural gas should not be neglected [22,23]. However, the benefits have resulted in growing interest in developing methods to renewably produce methane at prices that can compete with conventional natural gas [24]. Various technologies have emerged from this development, with catalytic methanation being the most extensively investigated [25,26]. Moreover, biological methanation has been established as a promising means of generating renewable methane [26,27]. Additionally, as part of this review, we investigate the techno-economics of bio-electrochemical methanation (electromethanogenesis) and the methanation through direct eCO_2RR. Although these technologies are not as technologically mature as catalytic and biological methanation, they possess unique advantages that could make them appealing alternatives in the future.

3.1. Catalytic methanation

An in-depth analysis of the techno-economic parameters is

imperative for evaluating the economic feasibility of catalytic methanation. Several sources provide detailed insights into the techno-economics of this process within a PtX framework, either through simulation of a plant using software such as Aspen Plus®, or by analyzing the actual cost and efficiencies of demonstration projects.

Fig. 1 visually depicts the projected investment costs for the catalytic methanation reactor, excluding the H_2 production step, for different years as well as its efficiency.

Substantial investment cost reductions are anticipated in the future for catalytic methanation through the continued deployment of demonstration projects and large-scale facilities across many countries. This trend is confirmed by Fig. 1, which showcases the cost decrease across various sources. The analysis of the dataset highlights the considerable variance between different publications regarding the investment cost estimates for a specific year. This wide dispersion of values is typical for technologies that are still in the early stages of commercialization or exhibit lower technology readiness levels. Additionally, other factors contributing to this variance include the year of publication and implicit assumptions made within the respective publications, such as the size of the methanation unit, where economies of scale become important, as well as assumed process efficiencies. The right panel of Fig. 1 shows that indeed, the assumed size of the plant can explain parts of the decrease in investment costs. However, since plant investment costs seem to not only correlate with the size of the project but also with the year of commissioning, as visible by plants that will be commissioned in 2050 exhibiting generally lower costs than their counterparts commissioned in 2020, scaling effects alone cannot explain the decrease in costs fully but also learning effects seem to come into play. Nevertheless, the publications generally agree on an investment cost decrease over time projecting a more economically viable methanation reactor in the energy system of the future. However, although the investment costs of the catalytic methanation reactor are pivotal to the viability assessment of a catalytic methanation plant, a major proportion of costs is also attributed to the H_2 electrolyzer and electricity required for the electrolysis process. For example, Bellotti et al. (2022) calculated that the combined capital and operational expenditures of a PEM electrolyzer as part of a methanation plant makes up 39.7 % of the total plant cost. Furthermore, they state that the electrical energy cost needed to power the plant contributes with 50.6 % to the overall costs. Therefore, in order to enhance the economic viability of this process, minimizing electricity and electrolyzer costs is crucial [60–63]. Fig. 1 shows the large spread for efficiency values within different data sources. From the figure, it can be derived that no major improvements for the energy efficiency of the process are to be expected in future years. Utility consumption has been identified across various publications to be in the range of 0.007–0.05 kWh_{el}/kWh_{SNG} showcasing the large variance between sources [40,43,64].

The range for operational costs spans 1–11 $\%_{CAPEX}$ for this technology. Most values were reported within the range of 3–5 $\%_{CAPEX}$. While some publications consider operational costs to be independent of time [29,47], others anticipate a decline in operational costs over time [32,65]. However, we suggest an intermediate constant value of 4 $\%_{CAPEX}$ for all years, as most publications do not expect a relative change of operational costs with respect to CAPEX over time. The system lifetime has been frequently reported in the analyzed publications and is divided almost equally between a lifetime of 20 and 30 years. Hence, an intermediate value of 25 years is assumed. Publications that reported the lifetime over all support years generally did not indicate any variation between the present day and 2050 [29,47,66]. Therefore, the same value is assumed for all of the mentioned years. We suggest a TRL of 8, based on existing and planned projects for catalytic methanation and literature implying that catalytic methanation is close to full commercialization.

3.2. Biological methanation

In recent years, there has been less focus on the techno-economic aspects of biological methanation compared to catalytic methanation in the context of PtX which is supported by the analysis of publications obtained through the SCOPUS search, where only 36 out of 89 resources contained the term “bio” in their titles or abstracts. Consequently, the available techno-economic data for biological methanation is less extensive compared to catalytic methanation. Fig. 2 shows a similar decline in investment costs for biological methanation as for catalytic methanation. The cost reduction trend for biological methanation follows a similar trajectory as that of catalytic methanation, however with a larger cost reduction potential, which is not surprising considering the slightly lower TRL of biological methanation (TRL 7) and the anticipated benefits of maturation and scaling effects in the future. The approximately threefold decrease in investment costs for biological

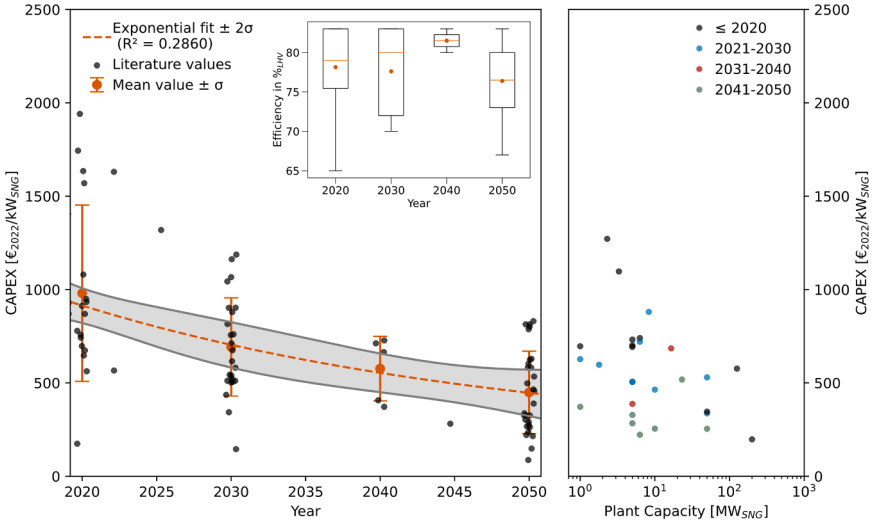

Fig. 1. Overview of the investment cost [12,18,19,28–51] and efficiencies [18–20,26,28,34,39,44,45,52–59] for catalytic methanation. The data points are slightly randomly displaced in x-directions to make overlapping data points visible. The grey area surrounding the exponential fit corresponds to the 95 % confidence interval of the exponential fit itself to show the uncertainty in the fit, whereas the orange bars correspond to the standard deviation of the values within a support year, demonstrating the large variance between the values from different sources. The right panel shows the dependency of investment cost on the plant size. For a detailed list of all values utilized in this figure, please refer to the supporting data.

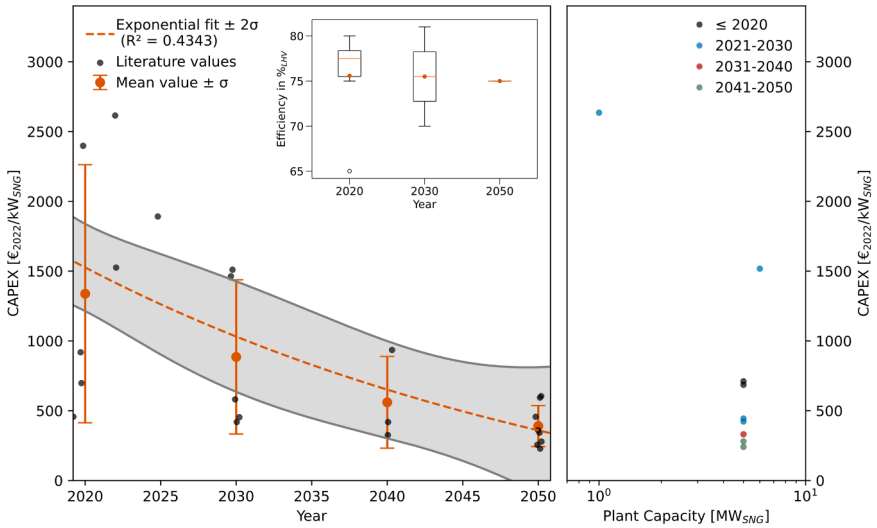

Fig. 2. Overview of the investment cost [12,19,31,40,48,53,54,68] and efficiencies [53,54] for biological methanation. The data points are slightly randomly displaced in x-directions to make overlapping data points visible. The grey area surrounding the exponential fit corresponds to the 95 % confidence interval of the exponential fit itself to show the uncertainty in the fit, whereas the orange bars correspond to the standard deviation of the values within a support year, demonstrating the large variance between the values from different sources. The efficiency in the top right corner only displays efficiency values for 2020, 2030 and 2050 due to the lack of further values in intermediate years. The right panel shows the dependency of investment cost on the plant size. For a detailed list of all values utilized in this figure, please refer to the supporting data.

methanation is necessary for it to become competitive with conventional natural gas. Literature data for scaling effects is less readily available than for catalytic methanation. However, even though the decrease of investment costs with size cannot be discerned that clearly from the right panel of Fig. 2, the effect that the commissioning year has on the costs, is clearly visible. The efficiency of biological methanation is scarcely available compared to catalytic methanation. Only few publications have been identified which state efficiencies that are within the thermodynamic limit. Comparing the mean values for the efficiencies in the boxplot reveals, similarly to catalytic methanation, that the analyzed publications overall do not expect a significant increase in energy efficiency for biological methanation. Utilities for biological methanation are expected to be around 0.056 kWh_{el}/kWh_{SNG} [67].

The operational costs of biological methanation are not as frequently reported as the investment costs. However, they generally fall within a range of 1–12 $\%_{CAPEX}$, comparable to the operational costs of catalytic methanation with the majority of values being in the range of 1–5 $\%_{CAPEX}$. For example, the company Electrochaea estimates their operational costs at 3 $\%_{CAPEX}$ [69], whereas van Leeuwen & Zauner [70] estimated operational costs of 5 $\%_{CAPEX}$ in the STORE&GO project [70]. Similar to catalytic methanation, 4 $\%_{CAPEX}$ was assumed for all years. In terms of the lifetime of biological methanation plants, the available resources uniformly agreed on a 20-year lifespan [32,71–73]. We suggest no change in the lifetime between support years as there were no indications of variations in the analyzed publications.

3.3. Electromethanogenesis

While electromethanogenesis is not as technologically mature as other Power-to-Methane processes, efforts are being made to scale it up. For example, a 1000 L continuous flow microbial electrolysis cell has been developed by Cusick et al [74]. and companies like Electrochaea and Cambrian Innovation are working towards commercializing electromethanogenesis [75,76]. However, most research is still conducted at the laboratory scale, ranging from milliliters to liters, and many engineering challenges must be addressed [77]. Methane production rates reported in the literature range from 0.2 to 61.7 mmol $C/L_{cat}/day$ [78]. Due to the lack of research on demonstration plant scale and due to the pending upscaling of the technology, the TRL of electromethanogenesis is estimated to be around 3–4 [66,79,80] and the technology is expected to only mature by 2050 [66].

Due to the current focus on laboratory-scale experiments, there is limited availability of techno-economic reports for electromethanogenesis. The few existing reports are primarily based on lab-scale results and may undergo significant changes when considering the economics of scaled-up processes [81]. With respect to investment cost, to the best of our knowledge, there exists only a single publication by Beegle and Borole [82] that provide a techno-economic analysis of a bio-electrochemical electrolysis system. However, the main focus is the production of hydrogen instead of methane. Although these results serve as an initial reference for the investment and operational costs in electromethanogenesis, further analysis and cost reduction estimations are needed. Beegle and Borole [82] cite capital costs of 3110 $\$/m^3$ H_2, equivalent to around 970 €/kWh H_2 in their calculations. The operational costs are estimated to be approximately 12 $\%_{CAPEX}$ [82] which is relatively high but can be attributed to the technological immaturity of the process.

In terms of efficiency, the current-to-methane efficiency of electromethanogenesis has been reported to range from 20 % to 100 % [78,82]. For instance, Van Eerten-Jansen et al. reported a maximum energy efficiency of 51.3 % [83]. The large variance of the reported values can be attributed to the lack of standardization and the absence of industrial-scale reactors. The minimum theoretical electrical input required for the process has been determined to be 9.1 kWh/m^3, but practical applications suggest a higher value of around 18 kWh/m^3, as reported by Van Eerten-Jansen et al [83].

3.4. Direct eCO_2RR

Similar to electromethanogenesis, estimating the techno-economic parameters of eCO_2RR systems is challenging due to the lack of industrial-scale demonstration plants [84] and the absence of standard designs, with CO_2 electrolyzers primarily existing at the bench scale. Therefore, benchmarking is often employed to estimate techno-economic parameters using related electrolysis processes such as alkaline or PEM electrolysis. The parameters are adjusted with respect to the TRL difference of the respective technologies as demonstrated in various publications [84–88].

A significant number of studies focus on determining the investment costs of current CO_2 electrolysis systems. However, due to the technology's low level of maturity, there is a scarcity of reports that predict future costs. Therefore, Fig. 3 shows the investment costs of CO_2 electrolyzers based on the scenario (worst, central and best) and not with respect to the installation year. The investment costs significantly vary, especially for worst-case and central-case predictions. However, the best-case assumptions converge and fall across a small range of costs. In comparison with catalytic and biological methanation, the potential cost development of CO_2 electrolyzers is subject to greater cost reductions and uncertainty of the predictions considering a development from worst-case to best-case as a consequence of its lower technological maturity. No distinction between different products of CO_2 electrolyzers has been made as no clear trend towards higher or lower costs for certain products could be observed.

Conversly to the investment costs which could not be distinguished with respect to the product of the process, the efficiencies varied greatly depending on the product. Fig. 4 shows the energy efficiency of CO2 electrolysis for different products. The efficiency was calculated by multiplying the faradaic efficiency with the voltage efficiency, as these values were most often readily available in the publications. The values needed for the voltage efficiency were retrieved from the publications themselves.

Similarly to the investment costs, also efficiencies were not provided with respect to a certain year. Therefore, we suggest using the lower quartile of the efficiency boxplot value for current efficiency predictions, the higher quartile for long-term predictions and to interpolate between those values for near-term efficiency predictions.

The reviewed literature predominantly agrees on a value for operational costs of 2.5 $\%_{CAPEX}$, as employed in various sources [86,89,109]. Hence, we choose this value and assume that it remains unchanged, similar to other analyzed technologies. The current density of CO_2 electrolyzers ranges from 300 to 1000 mA/cm^2 [94–96,102,107,110]. With the advent of new catalyst materials, it is expected that these numbers will increase by 2030. The cell voltage currently falls within 2.5–3.5 V, with an expected decrease in the coming years as research continues exploring methods for reducing overpotential. The lifetime suggested in most publications is 20 years. Therefore, this value is employed in the context of this review's suggestions. Electrolyzer efficiencies vary significantly between different publications. Whereas Fernández-González et al. (2022) [94] see an energy efficiency of 24.5 % and 52.1 % as reasonable values for realistic and optimistic assumptions, Spurgeon et al. (2018) [102] estimate higher energy efficiencies of 48 %, 72 % and 87 % for pessimistic, realistic, and optimistic scenarios, respectively. Energy system modelers are advised to consider

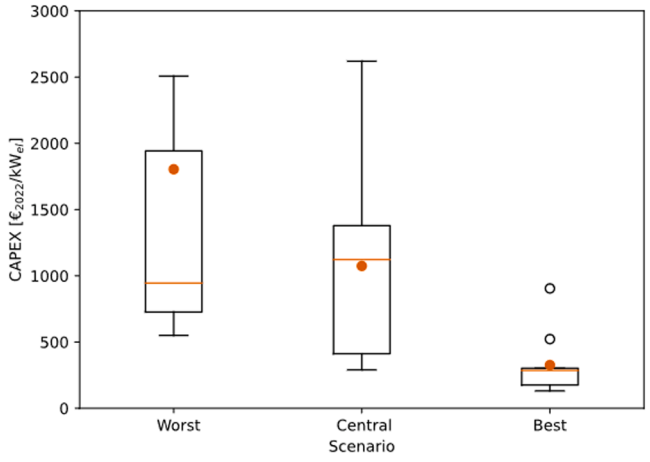

Fig. 3. Overview of the investment costs [84–95] of eCO_2RR. The boxplot is divided with respect to the scenario stated in the publication. For a detailed list of all values utilized in this figure, please refer to the supporting data.

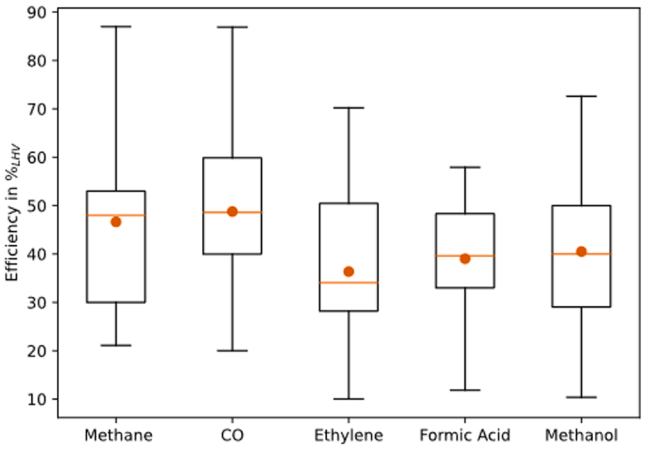

Fig. 4. Overview of the energy efficiencies [84,86,90,94–108] for various products of CO2 electrolysis. For a detailed list of all values utilized in this figure, please refer to the supporting data.

the upper percentile of the efficiency predictions only for parameters concerning the year 2040 and onwards.

4. Power-to-Syngas

Syngas, a mixture of carbon monoxide (CO) and hydrogen (H_2), plays a pivotal role in various PtX processes and its generation can significantly contribute to their capital costs [111]. As a crucial chemical and energy vector, syngas serves as a starting point for the production of many advanced chemicals and fuels such as ammonia, methanol, Fischer–Tropsch (FT)-based ones, and many more [112–114]. This reflects the large market size of over $200 billion in 2023 [115]. Moreover, the global syngas market is anticipated to experience significant growth [113], with estimations suggesting an expansion of over 30 % by 2026 [115].

The advantage of utilizing syngas as an energy vector and PtX product is existing infrastructure and demands, as syngas is already widely used in both the chemical and fuel industries [114]. However, so far, syngas primarily is produced from fossil resources [112] through processes such as steam-methane reforming (SMR) [116] or partial oxidation (POX) [117] driving its market price down. With approximately 0.2 $/kg, syngas proves to be relatively inexpensive compared to other PtX chemicals, posing a challenge for novel technologies to compete with these costs [116]. Currently, estimates for renewable syngas indicate higher values by nearly an order of magnitude [116], although these costs are expected to decrease as the technology matures [118].

Two specific novel technologies that are able to produce climate-friendlier syngas are the reverse–water–gas shift (RWGS) reactor and the co-electrolyzer. These technologies are analyzed in more detail below.

4.1. RWGS reaction

Economic data on the capital costs of RWGS reactors is still scarce in literature [119]. RWGS reactors are seldom seen in literature as independent units and are instead integrated into the cost estimates of synthesis reactors, e.g., in FT synthesis as in Tremel et al. (2015) [120], Schmidt et al. (2018) [121], and Grahn et al. (2022) [44]. This explains the lack of techno-economic data for a technology with a relatively high TRL. Marchese et al. (2021) [122] estimate the capital costs of the RWGS unit at 32 mil/$ for a unit producing 43 t/h, which can be translated – under the assumption of 8000 h of operation per year – to 563 $/kW, and Trinomics and Dechema [123] estimated a value of 36 €/t_{syngas}. Furthermore, Detz (2019) estimated the costs at 5.00 M€$_{2016}$/PJ$_{CO}$ (≈

370 €$_{2022}$/kW$_{syngas}$) in 2020, 4.00 M€$_{2016}$/PJ$_{CO}$ (≈296 €$_{2022}$/kW$_{syngas}$) in 2030, and 3.00 M€$_{2016}$/PJ$_{CO}$ (≈222 €$_{2022}$/kW$_{syngas}$) in 2050 considering plants at comparably large scales of 3–10 PJ/year (≈100–330 MW) [124]. However, such few values are not necessarily representative of the actual costs of such a reactor. Therefore, energy system modelers are generally advised to model RWGS reactors as an integrated process with other synthesis processes utilizing syngas, as more techno-economic data is available for integrated systems.

According to a report by Concawe [125] and a study by Detz (2019) [124], the energy efficiency of the RWGS reaction is currently estimated to be around 83 %. However, this value can vary significantly in literature depending on the assumptions of necessary heat input and CO2 selectivity. An aggregation of different publications summarized by Detz (2019) [124] reveals a range of 64–100 % and CO2 selectivity can reach up to 100 % [126]. The electricity consumption was estimated to be between 1.16 and 1.98 kWh$_{el}$/kg$_{input}$ by Comidy et al. (2019) [127] and the heat demand around 1.22 kWh$_{el}$/kg$_{syngas}$ [128]. The lifetime of a RWGS reactor is estimated at 25 years [124] and the operational costs can be estimated at 3 %$_{CAPEX}$ [124]. All in all, despite data for the RWGS reaction not being abundantly available, the technology is currently more mature than co-electrolysis [129], another method of producing syngas from carbon dioxide.

4.2. Co-electrolysis

Due to the similarities in process design, the techno-economic parameters for co-electrolysis are often derived from values for SOECs. However, it is important to note that co-electrolyzers incur approximately 30 % higher capital costs than SOEC units [127], primarily due to the need for CO_2 gas-handling and mixing systems [116]. Consequently, when no direct literature data for co-electrolyzers is available, SOEC CAPEX data is appropriately adapted, accounting for the differences in setup.

Fig. 5 illustrates that co-electrolyzers still exhibit high capital costs. Nevertheless, a similar cost decrease as that observed in water electrolysis, with projected reductions of 50–70 % in the medium to long term can be anticipated [113,130]. This cost decrease is attributed to the high potential learning rates of the technology, estimated at around 27 %, surpassing the anticipated learning rates of many other PtX technologies such as alkaline electrolyzers, proton exchange membrane (PEM) electrolyzers, methanol synthesis plants, or FT plants [116]. To enhance the economic viability of the process, improving the current density and reducing the cell voltage required for the reactions is crucial in order to minimize the significant electricity-related costs [86,101,131]. Additionally, capital costs for electrolyzers must be reduced along with CO_2 capture costs [113]. In Fig. 5, the costs based on estimates for SOECs are included to complement the co-electrolyzer data in order to be able to make more accurate recommendations for adequate values in the future. The relatively low co-electrolyzer CAPEX in 2022 frequently correspond to best-case assumptions without specific indications in the publication of when these assumptions become reasonable values. The right panel of Fig. 5 shows similar size effects as observed for other technologies. Again, the investment costs fall significantly as the size of the electrolyzer increases. However, when focusing on a single plant capacity value such as 10 MW, the spread in the investment cost values for this plant size clearly depends on the commissioning year, supporting the argument that not only plant size contributes to the reduction of investment costs but also different effects such as technological learning. Due to the lack of plant size data for co-electrolyzers, the data in the right panel primarily shows the investment cost – capacity dependency of standard SOEC cells. However, due to the similarity in process setup, a similar scaling-related behavior is expected to occur for co-electrolyzers.

Additionally, efficiency values for co-electrolysis are seldomly found in literature. To be able to extrapolate the expected efficiency development of co-electrolysis (red line), the value for 2020 was compared to the mean value for the efficiency of a standard SOEC in 2020 and was progressed similarly as the mean values of the boxplot for the efficiency of standard SOEC would suggest.

The fixed OPEX were assumed to be constant over time and are estimated to be 4 %$_{CAPEX}$ as a conservative intermediate value between 3 %$_{CAPEX}$ and 5 %$_{CAPEX}$, the most common values in the literature for both co-electrolyzers and SOECs [45,138,149,150].

5. Power-to-Methanol

Methanol is a versatile chemical compound that can be used as a platform chemical for many different chemical processes, such as the production of olefins (e.g., through MTO), DME and acetic acid but also

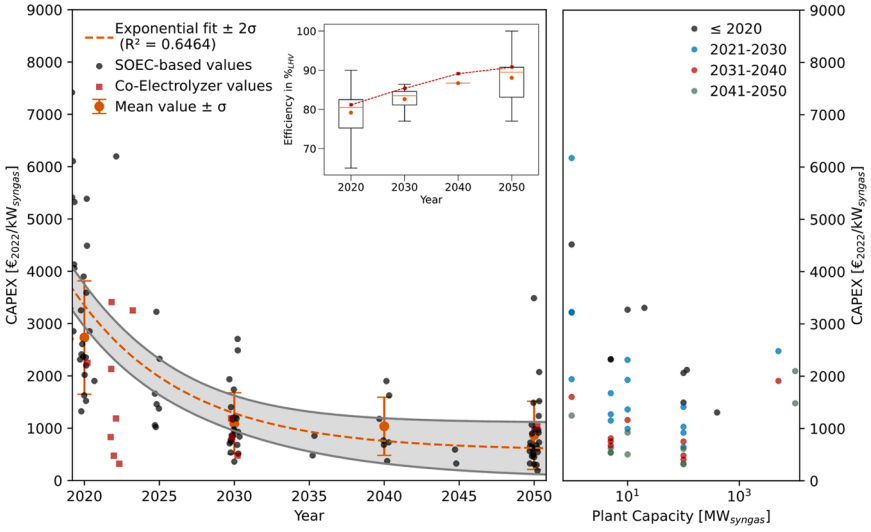

Fig. 5. Overview of the investment cost [12,25,31,43,45,54,115,116,125,132–145] and efficiencies [2,43,44,46,53,116,125,134,135,142,143,146–148] for co-electrolysis. The data points are slightly randomly displaced in x-directions to make overlapping data points visible. The grey area surrounding the exponential fit corresponds to the 95 % confidence interval of the exponential fit itself to show the uncertainty in the fit, whereas the orange bars correspond to the standard deviation of the values within a support year, demonstrating the large variance between the values from different sources. SOEC-based values were multiplied with 1.3 to account for higher expected capital costs according to Comidy et al (2019) [127]. The right panel shows the dependency of investment cost on the plant size. For a detailed list of all values utilized in this figure, please refer to the supporting data.

directly used as a fuel or fuel blending [151]. Although the production capacity reached around 148 Mt/year in 2019, the capacity is expected to double to a value of 311 Mt/year by 2030 [152]. This substantial demand, which is satisfied primarily through conventional production processes, is responsible for a large proportion of greenhouse gas emissions in the industrial sector with approximately 300 Mt_{CO2} emitted per year [153]. As many plants are bound to be retrofitted over the next 10–15 years, the discourse regarding refurbishing them in favor of renewable methanol production has increased [152]. In this context, the term "methanol economy" has arisen, which describes an economy based around methanol as an energy carrier, storage capacity, or feedstock to be used in a variety of sectors being generated renewably [154]. Indeed, amongst many different fuels, methanol is particularly well-suited because of its low production cost–to–market price ratio [155] and has been determined to be one of the best possible CCU pathways for mitigating greenhouse gas emissions [156]. Furthermore, methanol is easy to handle, even compared to methane [157]. However, in order to establish such a methanol economy, the Power-to-Methanol processes must improve in terms of their maturity and production costs. In fact, under current economic and political circumstances, no Power-to-Methanol process can yet compete with conventional fossil fuel–based processes [104]. In the following, some of the most important means of producing methanol with low carbon emissions will be investigated in the context of their techno-economic parameters.

5.1. Direct CO_2-Hydrogenation

The investment cost estimations for the methanol synthesis unit, meaning the core reactor unit, as part of the direct CO_2 hydrogenation of methanol are summarized in Fig. 6.

Conversely to methane-producing processes, fewer publications are to be found in which the costs of methanol are projected through 2050. More frequently, detailed pilot plant designs are suggested, and their techno-economic aspects are calculated based on current market conditions. Although a decrease in investment costs over time is observable, the extent of the reduction is lower compared to previously investigated processes. However, the spread of values remains considerably large indicating that many sources also anticipate lower investment costs in future years than the exponential fit to the data would suggest. The investment cost of CO_2 hydrogenation, similar to catalytic methanation, is primarily influenced by the cost of the water electrolyzer and the electricity required. Notably, sources indicate that the cost of electricity alone accounts for up to 70 % of the total production cost of methanol [44]. In comparison, the costs associated with the methanol synthesis unit and total CAPEX of the plant in general are relatively smaller [44, 153,170]. Comparing methanol synthesis unit CAPEX with electrolyzer CAPEX reveals, similar to what have been observed for catalytic methanation, a sevenfold higher cost percentage of the electrolyzer to the total plant costs [52]. In addition to cost reductions over time, cost reductions with respect to capacity play a significant role [148]. For instance, Brynolf et al [45]. proposed a decrease in costs from 1000 €/kW for a 5 MW plant to 300 €/MW for a 200 MW one. However, Schemme et al [158]. demonstrated that cost reduction is expected to diminish for plants larger than 200 MW due to the absence of economies of scale, necessitating the operation of multiple units in parallel instead of constructing larger ones. Therefore, plant scale has been identified as a critical parameter, alongside electrolyzer costs, in determining the feasibility of renewable methanol production via direct CO_2 hydrogenation [156]. This is showcased in the right panel of Fig. 6, which demonstrates the correlation between plant size and investment costs although the commissioning year again also contributes to the cost reductions. Under current market conditions, the price of methanol production throughout this process remains higher than the prevailing market price [170]. However, considering the potential inclusion of selling the byproduct oxygen in the electrolysis process or regulatory measures such as carbon taxes, the direct CO_2 hydrogenation process can become economically–viable, even under current conditions. Further advancements in technology, economies of scale, and cost reduction efforts are expected to enhance its economic viability in the future [111].

The boxplot of the efficiency shows that no significant increase in efficiency for future years is expected among most of the publications, therefore no improvements are assumed herein. Electricity for utilities is accounted for in the efficiencies of the boxplot. Frequently, publications do not specify the electricity for utilities. However, among those publications that include this electricity demand, it can be determined as 0.27 ± 0.14 kWh/kg_{MeOH} [146,157,162,168,169,171,174]. In general, efficiency can be increased through further heat integration within the methanol process chain. None of the analyzed literature sources indicate a decrease in fixed OPEX over time and the costs range between

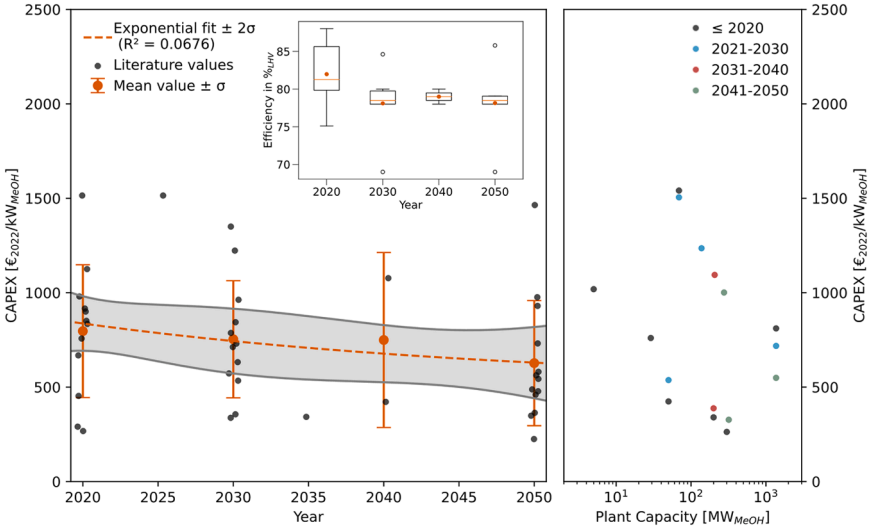

Fig. 6. Overview of the investment cost [41–45,47,59,121,125,158–161] and efficiencies [42,44,47,59,146,157–159,161–175] for CO_2-hydrogenation to methanol. The data points are slightly randomly displaced in x-directions to make overlapping data points visible. The grey area surrounding the exponential fit corresponds to the 95 % confidence interval of the exponential fit itself to show the uncertainty in the fit, whereas the orange bars correspond to the standard deviation of the values within a support year, demonstrating the large variance between the values from different sources. The right panel shows the dependency of investment cost on the plant size. For a detailed list of all values utilized in this figure, please refer to the supporting data.

2 $\%_{CAPEX}$ and 5 $\%_{CAPEX}$. We suggest an intermediate value of 3 $\%_{CAPEX}$. The lifetime of the methanol synthesis unit can vary between 20 and 30 years, depending on the publication. Considering its similarity to catalytic methanation reactors, we suggest a lifetime of 25 years.

5.2. CAMERE process

Due to the limited recognition of the Carbon Dioxide Hydrogenation Process for Methanol Production via RWGS reaction (CAMERE) process compared to direct CO_2-hydrogenation, particularly as a consequence of the disadvantages mentioned in the technology description in the appendix, there is a scarcity of publications providing techno-economic data, especially regarding the costs of the CAMERE process. Anicic et al [176]. are amongst the few authors to have conducted a techno-economic analysis of a CAMERE plant in a publication. They compare the CAMERE plant with one based on direct CO_2 hydrogenation. The CAMERE plant produces 607.6 t_{MeOH}/day and, according to their findings, based on the assumed total investment costs, a CAPEX of 6.34 $/$t_{MeOH}$ can be calculated. However, among the analyzed publications no data could be found giving cost predictions until 2050. The operational costs for the CAMERE process were determined based on the work of Anicic et al. [176], who used the same value as for the direct CO_2 hydrogenation. Therefore, a value of 3 $\%_{CAPEX}$ was utilized in this estimation, in accordance with the estimation made in the prior chapter. The energy efficiency of the CAMERE process is generally lower than that of direct CO_2-hydrogenation, primarily due to the energy-intensive RWGS step. Cho et al. (2021) estimate the overall process efficiency to be 38 % [177].

6. Power-to-Synfuels

Synthetic fuels, also known as synfuels or e-Fuels, offer an appealing solution to address carbon emissions in sectors where the transition away from conventional fossil fuels poses challenges. The synfuels category encompasses synthetically–produced gasoline, diesel, and kerosene, which can be seamlessly integrated into the automotive and aviation sectors as a so-called 'drop-in fuel' [178,179]. Substituting traditional fuels with synfuels has the potential to achieve CO_2 reductions ranging from 70 % to 96 % compared to the continued use of traditional fuels [41]. However, the viability of synthetic fuels as a more sustainable fuel production alternative largely depends on the composition of the electricity mix used in their production. If the electricity mix primarily relies on fossil-based electricity, for example, synthetic diesel produced via the FT process is estimated to yield emissions comparable to conventional diesel [180]. Nevertheless, significant emissions reductions are anticipated under suitable conditions [180,181].

Furthermore, synfuels can serve as a practical option for hydrogen transportation and storage due to their ease of handling and storage. Additionally, they benefit from existing infrastructure [41]. However, at present synfuels face cost competitiveness challenges when compared to conventional processes [41] and exhibit lower efficiencies, particularly in contrast to other alternatives like hydrogen or electricity. Nonetheless, in sectors such as aviation, where energy-dense fuels are essential, they can play a pivotal role [41]. Economic forecasts predict a decrease in the cost of synfuels to approximately 1–3 €/l without taxes, potentially enabling cost competitiveness with present fossil fuels [160, 182–184].

The FT synthesis, a well-established method for producing long chain hydrocarbons from syngas, currently stands as the only mature technology for producing a variety of synfuels [158]. Additionally, although it is theoretically possible to directly synthesize fuels through the electrochemical reduction of carbon dioxide (eCO_2RR), most eCO_2RR studies concentrate on producing short chain hydrocarbons [1]. Therefore, this pathway is not further investigated in this paper.

6.1. Fischer-Tropsch Synthesis

The availability of techno-economic information pertaining to the FT process is more abundant compared to other technologies under investigation because of the mature state of the FT process. However, for the purpose of this review, the focus was primarily placed on publications that link FT synthesis to a Power-to-Fuel process, thereby predominantly utilizing data from such sources. Fig. 7 presents an overview of the investment costs associated with the FT process.

Of the different studies aggregated in Fig. 7, it is notable that when providing CAPEX estimations, different authors use different system boundaries of what is considered within the FT unit. Although many authors include the RWGS reactor in the FT unit and consequently in the CAPEX, other sources also include the refining unit or solely the FT reactor. Equally often, no further context as to what is considered within the FT unit is provided. The different cases are represented in Fig. 7 with different colors. It is evident that in light of additional process steps, such as the RWGS unit or refining, generally add to the projected CAPEX, although there are also examples that exhibit lower costs. This is primarily caused by a difference in plant size or the comparison of a 'best case' scenario with a 'worst case' one. This also explains the wide range of different CAPEX estimates, especially for FT synthesis units, including the refining steps, as studies frequently implement a sensitivity analysis ranging from perfect market conditions to detrimental ones. However, the overall costs are not heavily influenced by including the RWGS reactor in the calculation, as it only makes up around 10–20 % of the CAPEX of the FT synthesis unit [187–189]. Similarly to other PtX technologies, the provision of H_2 can cause the largest variations in viability for Fischer-Tropsch products. Zhang et al. (2019) show that H_2 price can have a larger influence than factors such as CO_2 price, utility costs or CAPEX [190]. Analyzing CAPEX estimations for plants of similar sizes reveals a cost reduction that is akin to other technologies. It can be inferred that these cost reductions primarily stem from the maturation of the RWGS process and improvements in the standardization of the FT reactor, as well as scaling effects [47]. The effect of larger-scale plants is visualized in the right panel of Fig. 7, where a clear trend towards lower costs with larger plant sizes is discernible. However, as there seems to be a heuristic correlation between the plant size and the commissioning year, it remains difficult to attribute the extent of scaling effects and learning effects to the cost reduction trend. All in all, the expected cost reduction is not projected to be as significant as that in other technologies due to its high level of technological maturity [47].

The efficiency values displayed in the boxplot refer to the efficiency from hydrogen to synthetic fuel, therefore including the RWGS reactor as well as the FT plant and upgrading of the synthetic crude oil in the process. A slight increase in efficiency can be observed, presumably due to the maturation of the RWGS reactor and the integration improvements between different process steps. Unless otherwise stated, these efficiencies include the electricity consumption for utilities, which are seldomly displayed individually. Among the publications which include electricity demand for the reaction, a value of 0.052 ± 0.027 kWh_{el}/kWh_{fuel} could be determined [59,135,191]. Most studies assume a lifetime of 25–30 years for FT plants [44,135,141,191]. A 30-year lifetime was adopted for this analysis. Fixed operational costs are typically reported in the range of 3 %–5 $\%_{CAPEX}$ [36,41,43,53,59,116,135,141,190, 192]. We consider a conservative estimation of 4 $\%_{CAPEX}$, which will remain constant until 2050.

7. Power-to-Ethylene

Ethylene (C_2H_4) holds a significant position as one of the most widely used platform chemicals in industrial settings [66]. It serves as the foundation for numerous essential polymers, particularly in the plastics industry, including polyethylene and further products such as ethylene oxide, vinyl acetate and ethylene glycol [193]. Consequently, the production capacity of ethylene is substantial, reaching approximately 190

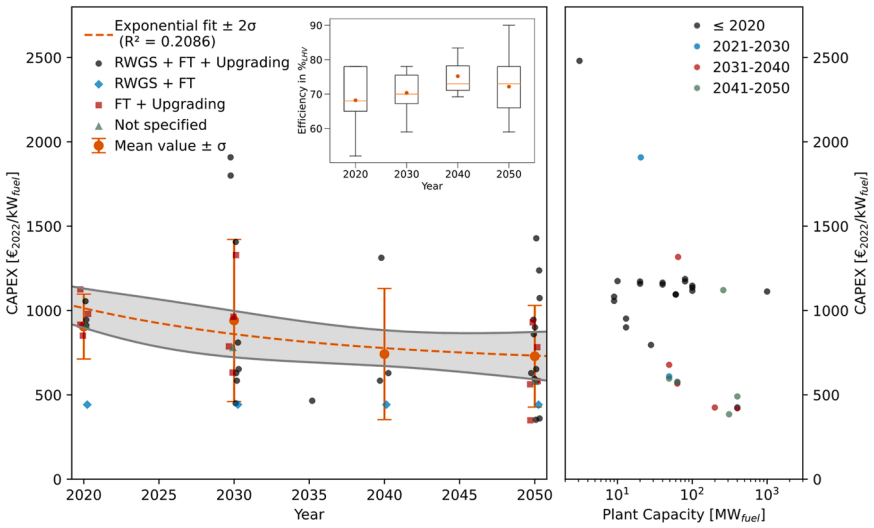

Fig. 7. Overview of the investment cost [41,43,44,47,51,120,121,134,135,140,159,160,185,186] and efficiencies [43,44,128,159] for Fischer-Tropsch synthesis. The data points are slightly randomly displaced in x-directions to make overlapping data points visible. The grey area surrounding the exponential fit corresponds to the 95 % confidence interval of the exponential fit itself to show the uncertainty in the fit, whereas the orange bars correspond to the standard deviation of the values within a support year, demonstrating the large variance between the values from different sources. The literature data is divided with respect to how much of the process chain is included for a certain CAPEX value (e.g., RWGS reactor, FT synthesis unit and refining step). Variations in the data not only come from different publications but also from sensitivity analyses including best, worst, and base case scenarios for the projected CAPEX. The right panel shows the dependency of investment cost on the plant size. For a detailed list of all values utilized in this figure, please refer to the supporting data.

Mt in 2019 and is projected to grow and reach up to 311 Mt by 2030 [152].

Traditionally, ethylene is obtained via the steam cracking of naphtha, a process conducted under severe conditions involving high pressures and temperatures ranging from 800 to 900 °C [193]. These harsh conditions result in the release of approximately 2–3 tons of CO_2 per ton of ethylene produced, leading to net global annual process emissions of approximately 200–300 Mt CO_2 [88,100,194]. If conventional processes continue to be used, it is anticipated that these emissions will increase to nearly 500 Mt CO_2 by 2030 [88].

Ethylene holds a higher price range, typically between 600–1200 $/t, depending on the production region. This higher pricing compared to methane and methanol, along with the substantial market size, makes ethylene an attractive target for substitution via PtX processes [96,193]. The utilization of high-priced chemicals like ethylene can serve as a market entry strategy to progress and scale-up the technologies. Low-value chemicals for which the competition for cost-efficiency with conventional processes is even higher are then able to profit from this learning progress [90].

It is worth noting that in addition to the aforementioned methods, there are alternative pathways for renewable ethylene production, such as methanol-to-olefin synthesis (MTO) and oxidative coupling of methane (OCM) [90]. However, these pathways are third-level processes and are not encompassed in the definition of PtX adopted in this context. Nonetheless, they hold significance, and an extensive review and discussion of other ethylene production routes can be found in Klüh et al [87]. and Zhang et al. (2023) [189].

7.1. Direct eCO_2RR

Similar to hydrogen electrolysis, in eCO_2RR, the cost of electricity dominates the overall electrolyzer cost [10,101]. Furthermore, especially for eCO_2RR to ethylene, low product selectivities lead to high separation unit costs [85,101]. Additionally, the issue of carbonate formation significantly impacts the cost of ethylene production through eCO_2RR. A recent study by Jing et al [107]. suggests that addressing the carbonate formation problem alone could indirectly reduce production costs by 744–1698 $/ton, as it reduces electricity consumption and product separation costs [107]. Consequently, the technology currently remains too expensive to compete with conventional methods of ethylene production. However, a study by De Luna et al. (2019) [90] indicates that the process can become cost-competitive with energy efficiencies exceeding 60 %, and electricity costs, which are major contributors to overall expenses, below 4 cents per kWh. Furthermore, improvements in faradaic efficiency (> 80 %) and current density (> 1000 mA/cm^2) are necessary [97,195]. According to Xia et al. (2022) [195], such improvements could result in a cost reduction of up to 33 %.

A detailed discussion of the techno-economic parameters for eCO_2RR has already been made when the technology was discussed in the context of Power-to-Methane. Corresponding values explicitly for ethylene production are stated in Fig. 3 and are similar to the CAPEX values reported for CO_2-electroylsis to other products. Therefore, as a simplification for energy system modelers, the economic recommendations summarized in the previous chapter can also be used for eCO_2RR to ethylene apart from the TRL which is lower for C_2-products (at TRL=3) and the energy efficiency which depends directly on the product.

7.2. Tandem electrolysis

A benefit of the tandem electrolysis is that the electrochemical conversion of single-carbon products, compared to C_2-products, is already on track of being commercially set up [106]. Additionally, due to higher current densities and lower overpotentials needed in COR, the investment costs for the electrolyzer are lower [196]. Therefore, the tandem process has been labelled by various researchers as being economically beneficial compared to the direct CO_2-electrolysis [85,96].

The TRL of this technology is in principle slightly higher than for the direct CO_2-electrolysis. We can already utilize knowledge obtained for the reaction of CO_2 to CO or the electrolysis of CO, which is already more well-understood than eCO_2RR to ethylene [85]. Overa et al. (2021) attribute a TRL of 4 to the CO_2-to-CO electrolyzer and a TRL of 3 to the CO electrolyzer, suggesting an overall TRL of 3 for the tandem process according to common TRL conventions [197]. Commercially available devices based on solid oxide electrolysis for CO_2-to-CO electrolysis, such as those offered by Topsoe, already exist [198]. However, there are only a few publications studying and economically analyzing the tandem

process [85,96,199].

It is suggested to analyze the individual components of the overall process, namely the CO_2-to-CO electrolyzer and CO-to-Ethylene electrolyzer, separately with respect to their techno-economic parameters, as there are currently no publications in literature, to the best of the author's knowledge, that comprehensively investigate the integrated tandem process. Ramdin et al. (2021) [85] already conducted such an analysis and obtained a cost of 1250 €/kW for the CO_2-to-CO electrolyzer and 890 $/kW for the CO-to-ethylene one. Similarly, efficiencies, operational costs and technical lifetimes can be derived based on the individual electrolyzers that are part of this process chain.

8. Power-to-formic acid

Formic acid (HCOOH) is a chemical frequently used in the food industry, leather and textiles production, agriculture, and the pharmaceutical and chemical industries as a valuable feedstock [1,200,201]. Beyond its current applications, formic acid exhibits potential as an energy vector due to its capability to act as a hydrogen storage medium and its direct utilizability in formic acid fuel cells [202]. Formic acid possesses advantages such as low toxicity, low flammability, and ease of storage [203], which make its use as an energy vector attractive. Despite the smaller market size ($560 million in 2020) [204] compared to substances like ethylene [99], the formic acid market has seen growth in recent years [203,204], which is expected to continue and potentially accelerate with increasing adoption as a hydrogen energy carrier [90].

Conventional formic acid production follows four different pathways: hydrolysis of methyl formate, hydrocarbon oxidation, formamid hydrolysis, and direct preparation from formates [205]. However, these processes are based on fossil fuels and emit on average more than three tons of CO_2 per ton of formic acid produced [1]. A study by Gunasekar et al. (2016) [206] demonstrated that adopting a PtX approach to formic acid generation has the potential to reduce associated greenhouse gas emissions by a factor of 10 compared to these conventional processes. Consequently, two prominent renewable approaches for formic acid generation are discussed: direct CO_2 hydrogenation and direct eCO_2RR. While still in the development phase, these technologies show promise as cost-competitive alternatives to replace conventional formic acid production processes.

8.1. Direct CO_2 Hydrogenation

Techno-economic data regarding CO_2 hydrogenation to produce formic acid is limited in literature, and only a few techno-economic studies of the process have been identified in the structured literature research (see Figure A.7). Jarvis and Samsatli [13] calculate the CAPEX of the process around 57.57 £ /t (≈780 €/kW).[1] Operational costs are assumed to be similar to CO_2 hydrogenation for other products, such as methanol. Therefore, a recommended value of 3 $\%_{CAPEX}$ is proposed. Additionally, the lifetime of a CO_2 hydrogenation plant for formic acid is estimated at 20 years, in accordance with the recommendation of Jarvis and Samsatli (2018); similarly, their estimation for electricity consumption of 4.1 MWh/t is adopted herein [13].

As the technology matures, cost reductions are expected, but to the best of the author's knowledge, no papers discussing the future costs of CO_2 hydrogenation to formic acid are currently available. However, considering the process setup similarities with CO_2-hydrogenation to methanol, it can be assumed that cost reduction trends may exhibit similarities as well, although the higher current technological maturity of the methanol-related process must be taken into account. Consequently, the cost of formic acid CO_2-hydrogenation is anticipated to decrease more significantly between 2020 and 2030 and behave similarly to methanol starting from 2030.

Unlike the CO_2 hydrogenation of methanol, the TRL for the CO_2 hydrogenation of formic acid/formate is notably lower. A comparison of different publications reveals a range of 2–5 [207,208]. We estimate the TRL of this process to be 4. This estimation is based on the lack of attempts to integrate the process into a demonstration-scale plant and the scarcity of literature that deal with describing or simulating the process on a larger scale. In fact, a significant portion of recent publications on the topic[2] has focused on catalyst design and understanding the reaction mechanisms (corresponding to lower TRLs), with only a small fraction addressing reactor design or techno-economic process evaluation (see Figure A.7).

8.2. Direct eCO_2RR

Formic acid, as a product of direct eCO_2RR, holds the potential to be one of the most profitable CO_2-electrolysis products. Its production requires fewer electrons compared to ethylene or methane, and it exhibits a high faradaic efficiency (>90 %) [209]. In a study by Jouny et al. (2018) [86], it was calculated that formic acid, along with carbon monoxide, is one of the only potentially profitable products from eCO_2RR under their specific assumptions.

The techno-economic data for the direct CO_2 electrolyzer introduced in the chapter on Power-to-Methane is utilized here, and readers are referred to Fig. 3 for the relevant literature-based techno-economic data recommended for applications. Some sources outline differences between CAPEX and fixed OPEX for formic acid production compared to other products, as described by Jouny et al. (2018) [86] and, additionally, catalyst costs vary depending on the desired product; for instance, Au catalysts frequently used for carbon monoxide generation [210–213] are more expensive than Cu ones for ethylene production. However, over the entire scope of publications analyzed, as is shown in Fig. 3, no clear trend of higher or lower costs for a certain product was observed and it is assumed that the difference in catalyst material does not have a substantial effect on the CAPEX beyond the uncertainty already implied by different values from various sources. Therefore, similar values were applied for the analysis of techno-economic data. However, due to its simpler reaction mechanism and progress towards commercialization, the TRL can be assumed to be slightly higher than that of ethylene or methane [204,214,215]. Thus, a TRL of 5 is suggested.

9. Summary of recommendations

This review has analyzed several PtX technologies that include the utilization of CO_2 to form different value-added chemicals. Tables 1 and 2 summarize the techno-economic recommendations for these technologies.

10. Conclusions

Although the data foundation depends significantly on the technological maturity of the process and their anticipated benefits or relevance in political discourse, the investment costs are expected to decrease for all technologies by all of the publications analyzed. This is promising, considering the current status quo in which most of the analyzed technologies are not yet able to compete with conventional processes. However, the review also showed that besides improvements in the investment costs and efficiencies of the CO_2 utilization process, in many cases the economic viability of the process is highly dependent on the cost-effective provision of renewable hydrogen and, related to that, low electricity costs. Several sources across all CO_2-consuming Power-to-X technologies analyzed herein highlight the significant cost

[1] Assuming 8000 hours of operation per year, an average exchange rate of 1.1301 €/£ and a formic acid LHV of 5.4 MJ/kg

[2] Based on a SCOPUS literature search with the search key: "co2 hydrogenation formic acid"

Table 1
Overview of the techno-economic cost recommendations based on the analysis of the structured literature search.

	Investment Cost (CAPEX) [€$_{2022}$/kW]				Operational Cost (OPEX$_{fix}$) [%$_{CAPEX}$]
	2020	2030	2040	2050	
Catalytic Methanation[a]	960	750	560	450	4
Biological Methanation[a]	1450	950	600	370	4
CO_2-Electrolysis[b]	1800	1100	750	400	2.5
Co-Electrolysis[b]	3300	1300	800	600	4
CO_2-Hydrogenation (MeOH)[a]	810	750	700	630	3
Fischer-Tropsch[a]	1050	870	770	700	4

CO2-electrolyzer CAPEX is assumed to be similar irrespective of the product. As the publications mostly consider scenarios (worst, central, best) instead of explicitly stating the year for which the costs are valid, it was assumed within this table that "best-case" costs refer to long-term cost assumptions (2050), while "base-case" cost calculations refer to near-term cost assumptions (2030) and "worst-case" to the current status quo.

[a] Costs with respect to the product of the process

[b] Costs with respect to the electricity input.

Table 2
Overview of further techno-economic parameters aggregated based on the structured literature search. Due to the difference in efficiency based on the product of the CO2-Electrolysis, the efficiency is differentiated with respect to the products.

	Efficiency [%$_{Lhv}$]				Lifetime [a]	TRL
	2020	2030	2040	2050		
Catalytic Methanation	78	78	78	78	25	8
Biological Methanation	76	76	76	76	20	7
CO_2-Electrolysis (CH_4)	30	38	46	53	20	4
Co-Electrolysis	82	85	89	90.5	15	6
CO_2-Hydrogenation (MeOH)	82	82	82	82	25	8
Fischer-Tropsch	68	70	72	74	30	8–9
CO_2-Electrolysis (C_2H_4)	29	36	43	50	20	3
CO_2-Electrolysis (HCOOH)	32	38	44	49	20	5

proportion of the electrolysis unit within the entire Power-to-X process chain and emphasize the need for cost reduction in this realm to make these Power-to-X processes economically competitive with conventional processes. Furthermore, it has been shown that policy instruments such as CO_2 taxes and the valorization of byproducts can also help improve the economic viability of PtX technologies such that they can become competitive with conventional processes. Therefore, it is essential to further investigate which technology can have a positive impact on the future energy system and how the competition between technologies can cause lock-in effects or foster technology-overarching learning and establish which KPIs are especially decisive for the technology to become economically–attractive. Additionally, the immaturity of the processes leads to large variations in the future cost predictions between different sources and even for current costs, large discrepancies were observed. This makes accurate predictions difficult and highlights the importance of sensible sensitivity analyses to cover the wide range of possible future values given by different publications. Consequently, energy system modelers must to be aware of the lack of robustness of their scenarios based on the chosen assumptions for the PtX sector. This review has shown that significant gaps exist in the literature regarding the techno-economic analysis of certain PtX technologies that could become important in a future energy system that is primarily based on renewable energy. Such analyses are essential to be able to make cost predictions and determine the role of these technologies in the future energy system.

CRediT authorship contribution statement

Felix Kullmann: Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Detlef Stolten:** Supervision, Funding acquisition. **Jochen Linssen:** Writing – review & editing, Supervision, Conceptualization. **Gian Müller:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization.

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

During the preparation of this work the author(s) used ChatGPT 3.0 in order to improve language and readability. 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.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jcou.2025.103019.

Data Availability

The data supporting this article have been included as part of the Supplementary Information.

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