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Advancing E-fuels production through process intensification: overcoming challenges and seizing opportunities for a sustainable energy future - A critical review

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ABSTRACT

The global transition toward sustainable energy emphasizes e-fuels as a promising alternative to fossil fuels, particularly in sectors that are difficult to decarbonize, such as aviation and heavy industry. E-fuels are produced via the Power-to-Liquids (PtL) process, which converts renewable electricity into hydrogen through water electrolysis or other sources, such as methane or biogas reforming, followed by the synthesis of hydrocarbons and other carbon-based compounds using captured CO_2. Despite their potential, e-fuels face challenges such as high production costs and energy-intensive processes. Process Intensification (PI) offers a pathway to address these challenges by optimizing chemical processes to enhance efficiency, lower costs, and reduce environmental impact. Key areas of PI innovation include advancements in electrolysis technologies, catalyst development, reactor design, and carbon capture methods. These innovations are crucial for improving the efficiency of hydrogen and carbon-based fuel production, decreasing costs, and minimizing greenhouse gas emissions. Furthermore, PI facilitates modular and scalable production systems that integrate seamlessly with renewable energy sources, reducing the need for fuel transportation and associated emissions. This paper explores the challenges and opportunities presented by PI, emphasizing its critical role in advancing the production of e-fuels and positioning them as a key component of a low-carbon energy future.

1. Introduction

The increasing global demand for sustainable energy solutions has catalyzed significant advancements in the field of synthetic fuels, or e-fuels. These fuels, produced through the utilization of renewable energy sources to synthesize hydrocarbons, offer a promising alternative to traditional fossil fuels. E-fuels are primarily generated using renewable electricity to split water into hydrogen and oxygen through electrolysis. This hydrogen can then be combined with carbon dioxide, captured from industrial processes or directly from the air, to produce synthetic hydrocarbons. This Power-to-Liquids (PtL) process represents a versatile approach to energy storage and fuel production, leveraging renewable energy to create liquid fuels that can be used in existing infrastructure [9].

The potential of e-fuels to reduce greenhouse gas emissions is significant. By utilizing captured carbon dioxide, the overall lifecycle emissions of e-fuels can be substantially lower than those of conventional fossil fuels. Furthermore, e-fuels can enhance energy security by reducing dependence on imported fossil fuels and diversifying the energy supply. This is particularly important for regions without significant renewable energy resources but with abundant potential for carbon capture or renewable electricity generation.

E-fuels also provide a crucial pathway to decarbonizing sectors that are challenging to electrify. The aviation and maritime industries, for example, face significant hurdles in adopting battery-electric technologies due to the energy density required for long-haul operations. E-fuels, with their high energy density and compatibility with existing engines and fuel distribution infrastructure, offer a viable alternative to fossil fuels in these sectors [94]. Additionally, e-fuels can be used in the heavy-duty transport sector, where the limitations of battery technology, such as weight and charging time, make direct electrification less feasible [1].

As the urgency to transition towards a low-carbon economy intensifies, the role of e-fuels in the global energy landscape becomes increasingly pivotal. This urgency is underscored by international agreements and national policies aiming to limit global temperature rise and reduce greenhouse gas emissions. The Paris Agreement, for instance, sets ambitious targets for emission reductions, necessitating

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the rapid deployment of a wide range of clean energy technologies. In this context, e-fuels offer a complementary solution alongside renewable electricity and hydrogen, providing a flexible and scalable option for energy storage and fuel supply.

Moreover, the economic implications of e-fuels are considerable. The production of e-fuels can stimulate economic growth by creating new industries and jobs in the fields of renewable energy, chemical engineering, and carbon capture and utilization. Regions with abundant renewable resources or industrial CO_2 emissions could become hubs for e-fuels production, contributing to local economic development and providing new export opportunities [104]. Additionally, by stabilizing energy prices and reducing exposure to volatile fossil fuel markets, e-fuels can enhance economic resilience (Fig. 1).

However, the adoption of e-fuels is not without challenges. The production processes involved are currently energy-intensive and costly, primarily due to the high electricity requirements for electrolysis and the need for efficient carbon capture technologies. The development of more cost-effective and efficient production methods is essential to making e-fuels competitive with conventional fossil fuels [7,37]. This is where process intensification (PI) plays a crucial role.

PI refers to the strategies aimed at making chemical processes more efficient, compact, and sustainable. In the context of e-fuels production, PI is pivotal in addressing the existing challenges by improving the efficiency and economics of the production processes. PI can involve a variety of approaches, including the integration of advanced materials, innovative reactor designs, and novel process configurations that reduce energy consumption, enhance reaction rates, and optimize resource utilization [49,66].

One of the key areas where PI can have a substantial impact is in the electrolysis of water to produce hydrogen. Traditional electrolysis technologies are often limited by low efficiency and high costs. However, advances in materials science, such as the development of high-performance catalysts and membranes, can significantly enhance the efficiency of this process. Additionally, PI techniques such as microchannel reactors and high-temperature electrolysis can further reduce energy consumption and improve hydrogen yield.

Another critical aspect of PI in e-fuels production is the synthesis of hydrocarbons from hydrogen and CO_2. This step often requires high-pressure and high-temperature conditions, which can be energy-intensive. By developing new catalysts and reactor designs, PI can lower the energy requirements and increase the selectivity and yield of the desired products [56]. For example, the use of modular reactors and continuous flow systems can optimize heat and mass transfer, leading to more efficient reactions and reduced energy use.

Furthermore, PI can facilitate the integration of carbon capture and utilization (CCU) technologies with e-fuels production. This integration is essential to ensure that the carbon dioxide used in the process is sourced sustainably and does not contribute to net greenhouse gas emissions. Innovative approaches such as combined heat and power systems, which utilize waste heat from the electrolysis and synthesis processes, can improve overall energy efficiency and reduce operational costs.

The modularity and scalability of PI technologies also offer significant advantages for e-fuels production. Modular systems can be easily adapted to different scales of production, from small-scale facilities that serve local markets to large-scale plants that supply global demand. This

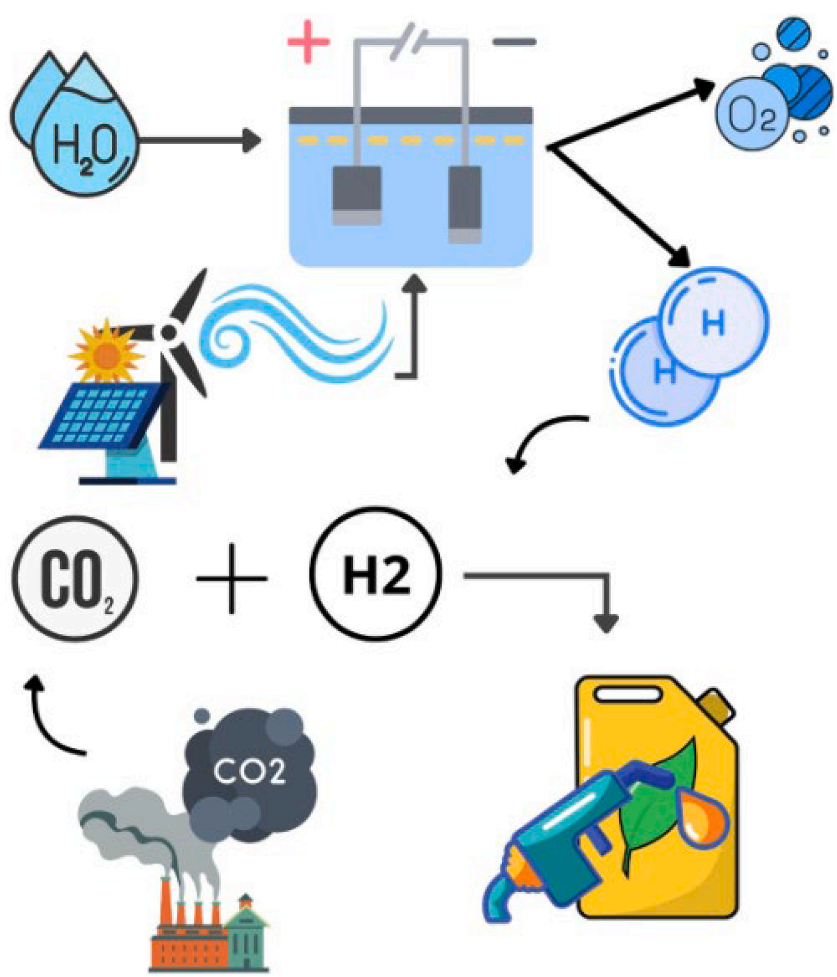

Fig. 1. E-Fuels as a green alternative to fossil fuels.

flexibility allows for a more distributed production model, reducing the need for long-distance transportation of raw materials and finished products, which further lowers the carbon footprint of e-fuels [123].

This paper will analyze the challenges and opportunities associated with process intensification in the production of e-fuels. It will explore how PI can make the production processes more sustainable by improving energy efficiency, reducing costs, and minimizing environmental impact. By examining the latest advancements in technology and the potential for future innovations, this paper aims to provide a comprehensive overview of the role of PI in the advancement of e-fuels as a key component of the global energy transition. Also, paper will also discuss the implications of PI for industrial scalability, economic viability, and policy development, offering insights into how these technologies can be effectively integrated into the existing energy infrastructure.

1.1. Context and background

Hydrogen production, along with carbon capture, utilization, and storage (CCUS), represents two key pillars in the effort to decarbonize and transition towards a net-zero emissions energy system, currently dominated by fossil fuels [114]. While these technologies face some technical hurdles and relatively high costs, their large-scale deployment is also constrained by the absence of midstream (transport, pipelines, storage, etc.) and downstream (engines, turbines, etc.) infrastructure that is compatible with hydrogen and CO_2, particularly at the scale required for widespread adoption. It is projected that the necessary infrastructure to support a global hydrogen economy integrated with CCUS will not be in place before 2030, despite the increasing social and regulatory pressure to decarbonize energy-intensive sectors [2]. The absence of suitable infrastructure for the extensive use of hydrogen and captured CO_2 could be mitigated, in part, by the production of sustainable liquid electro-fuels (e-fuels), synthesized from hydrogen and captured CO_2. These carbon-neutral e-fuels offer several advantages, including [37]:

(a) compatibility with existing storage and transport systems,
(b) suitability for use in current internal combustion engines in sectors like aviation, shipping, and freight without requiring modifications,
(c) low sulfur content and compatibility with fossil-based kerosene blends.
(d) potential for long-term economic returns due to the established market for fossil fuel-based counterparts and their role in reducing emissions from the transport sector.
(e) from a technological readiness perspective, e-fuels have already been produced at both pilot and industrial scales across the globe, demonstrating no significant technical barriers to their production. [11,94].

While hydrogen (H_2) can be directly utilized as a fuel, the large-scale infrastructure necessary to enable its widespread use is not yet fully developed. As a result, liquid electro-fuels (e-fuels) derived from H_2 and captured CO_2 present a promising alternative due to several key advantages [69]: (i) they are easier to store compared to gaseous or liquid hydrogen, (ii) they can be transported using the existing petroleum infrastructure, and (iii) they are fully compatible with engines and equipment in sectors like aviation, shipping, and freight, without the need for modifications [44,48,66,86].

Fig. 2 provides an overview of strategies for integrating H_2 production with low-carbon e-fuels derived from H_2, utilizing existing oil and gas infrastructure. Hydrogen can be generated either from fossil fuels or via electrolysis powered by renewable energy sources, such as electricity from geothermal reservoirs. Once produced, hydrogen can be directly applied in various sectors, as illustrated in Fig. 3. Alternatively, it can be combined with captured CO_2 and converted into e-fuels like e-methanol or e-kerosene, further expanding its potential applications in decarbonizing transportation and other industries. [16,75].

Table 1 provides a comprehensive overview of the major and cutting-edge hydrogen production and CO_2 capture technologies, categorized by their technology readiness level (TRL), which ranges from 1 (representing basic principle validation) to 9 (indicating a fully operational system demonstrated in a real-world setting). The subsequent section offer an in-depth analysis of these technologies, including detailed performance metrics and associated cost evaluations [94,105].

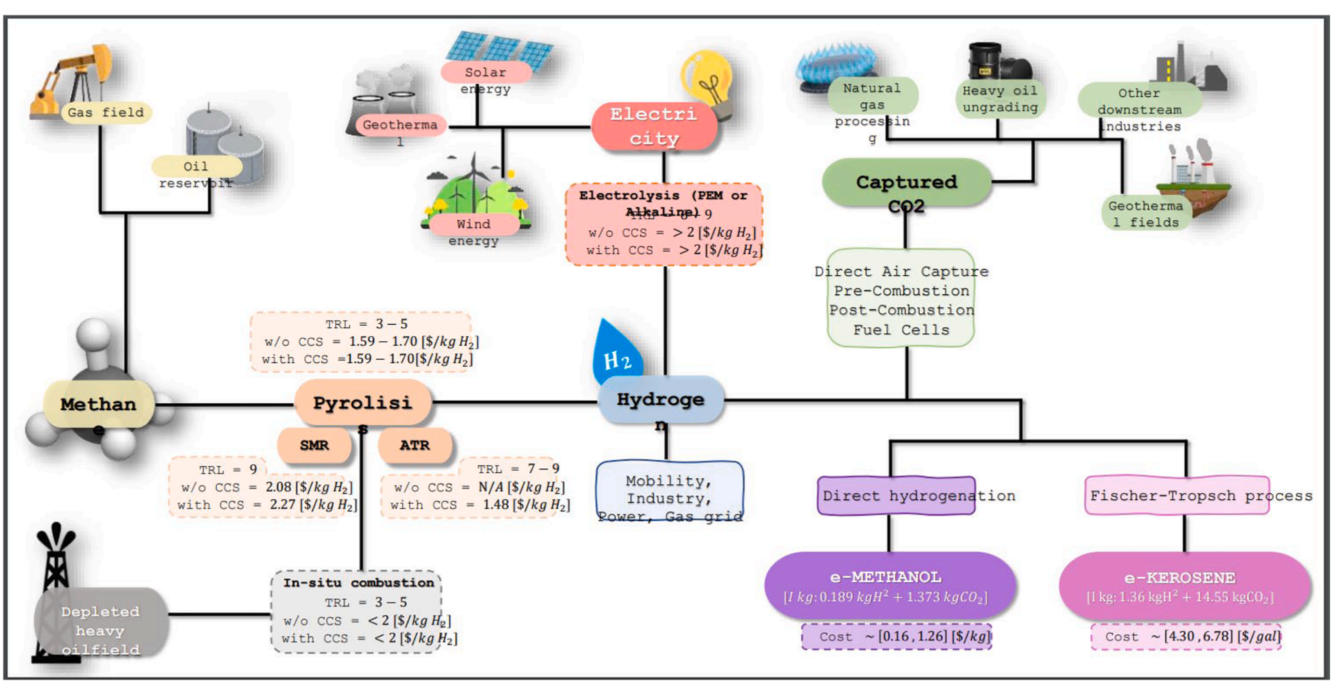

Fig. 2. Pathways for the incorporation of hydrogen into various sectors of the economy.

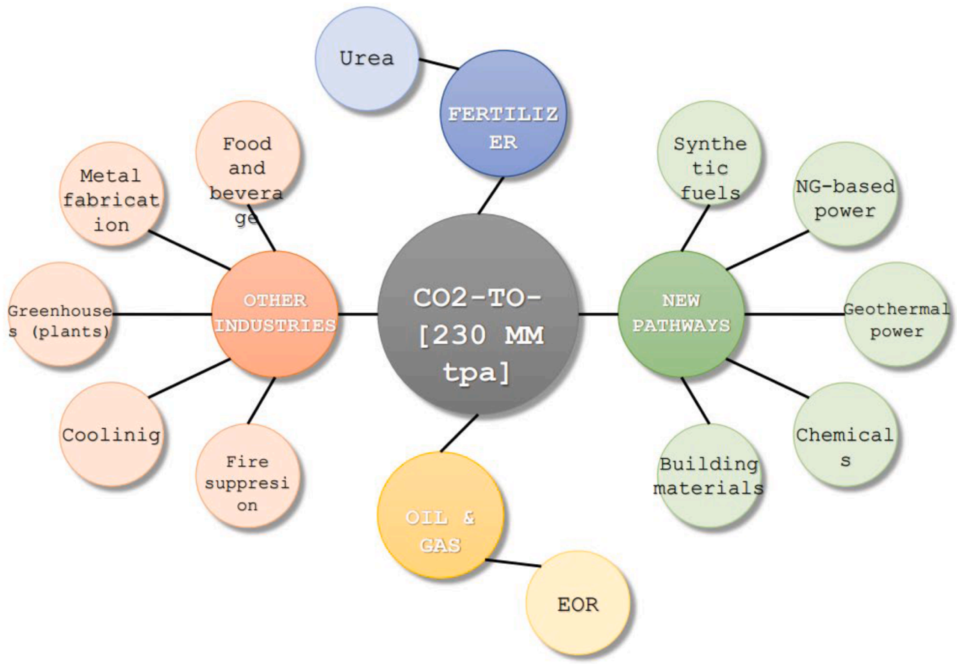

Fig. 3. Conversion of CO₂ into a valuable resource across different economic domains.

1.2. Comparison of hydrogen production technologies

Hydrogen production technologies expected to play a crucial role in large-scale hydrogen (H_2) generation, from short- to long-term, are outlined in Table 2. These methods are assessed based on their advantages, disadvantages, technology readiness level (TRL), and cost ranges. H_2 production is grouped into four categories: from fossil fuels, biomass and waste streams, water electrolysis, and natural sources [20,94,105]. a) Fossil fuel-based hydrogen can be produced via seven primary methods: coal gasification, steam reforming (or steam methane reforming when methane is the feedstock), plasma reforming, partial oxidation (POX), autothermal reforming (ATR), methane pyrolysis, and in situ combustion of underground reservoirs.

Steam Methane Reforming (SMR) with Membrane Reactors:

While conventional reactors are commonly used for H_2 production via SMR, membrane reactors offer the potential for enhanced energy and conversion efficiency. They may also lower production costs by enabling milder operating conditions. Process intensification strategies, such as membrane reactors that integrate multiple processes (e.g., reaction and purification) into a single unit, and the use of low-carbon energy sources (e.g., microwave heating, plasma), are key enablers [58]. b) Hydrogen production from biomass and waste streams can be achieved through three key technologies: dark fermentation, photofermentation, and gasification [3]. In water electrolysis, which involves splitting water into hydrogen and oxygen using electricity, three main techniques are employed: alkaline electrolysis, solid oxide electrolyzers, and polymer electrolyte membranes (PEM).

1.3. Electrolysis

Solid oxide electrolyzers, though at an earlier stage of technical development, achieve the highest efficiency by combining heat and electricity to generate hydrogen. Solid oxide electrolyzers consume the least electricity, while alkaline electrolyzers have the highest energy demand.

Startup Time: Among the three electrolyzer types, alkaline electrolyzers are the most mature in terms of technology. PEM electrolyzers overcome some of the limitations of alkaline electrolyzers, including integration with fluctuating renewable energy power systems and a faster response time. Most commercially-available PEM electrolyzers have input power limits of 5 MW and 10 MW as single units but these units can be grouped to form a bigger unit with a higher power limit [82].

Efficiency in Relation to System Size: A survey of commercially available alkaline and PEM electrolyzers across a range of system capacities (0.1 kW to 100 MW) revealed that efficiency improvements tend to level off once the system size exceeds approximately 100–300 kW for both types of electrolyzers (alkaline and PEM). This plateau in efficiency is likely attributable to the modular design of units beyond a certain scale. The highest efficiencies observed correspond to power consumption rates of approximately 50 kWh/kg for alkaline electrolyzers and 55 kWh/kg for PEM electrolyzers [32]. c) Lastly, hydrogen extraction from natural occurrences in geological formations, though less understood, presents a potentially cost-effective large-scale production option [122].

1.4. Comparison of CO_2 capture technologies

There are seven key carbon capture technologies, summarized in Table 3. The two most widely used are post-combustion capture and gas sweetening, largely due to their extensive industrial applications. In power plants, post-combustion technology captures CO_2 from flue gases using regenerative solvents, while natural gas processing facilities employ gas sweetening for CO_2 removal [54,94,96].

It has been demonstrated that post-combustion technology, specifically amine-based CO_2 absorption, achieves the highest CO_2 purity, although impurity levels can vary. The minimum energy required for CO_2 capture, as estimated using thermodynamic principles, increases steeply depending on the initial CO_2 concentration (Liu et al., 2022). For CO_2 concentrations between 0.4 and 0.05, the energy demand rises by approximately 11 kJ per mole of CO_2, and for concentrations below 0.05, the slope becomes much steeper at 220 kJ per mole [118]. In particular, capturing CO_2 from concentrated sources, such as coal gasification or flue gases from coal and natural gas combustion, typically requires between 1 and 4 kJ per mole of CO_2, while direct air capture (DAC), which deals with much lower CO_2 concentrations (around 0.04 % or 409 ppm), demands between 19 and 21 kJ per mole [118].

In terms of costs, carbon capture technology, which has been in use for around 15 years, can account for up to 40 % of a project's total

Table 1
Technology readiness level (TRL) for H_2 production and CO_2 capture technologies ([4,25,39,41,43,46,47,62,73,81,82,93,102,105,106,121,122]).

TRL	CO_2 capture technologies	H_2 production technologies
Actual system proven in the operational environment	Post-combustion amines (power plants) Pre-combustion NG processing (gas sweetening)	Alkaline electrolysis water-splitting Auto-thermal reforming Coal gasification Partial oxidation Steam reforming
Technology validated in the industrial environment	Dense inorganic membranes (H_2 separation for reformer)	Dark fermentation of biomass In situ combustion of hydrocarbon reservoirs Photofermentation of biomass Pyrolysis of methane Solid-oxide electrolysis water-splitting
Technology demonstrated in the industrial environment	Polymeric membranes (power plants and NG processing) Post-combustion biphasic solvents CLC CaL	Gasification of biomass Plasma reforming
System complete and qualified	Oxy-combustion gas turbine Pre-combustion PSA with cryogenic (liquid CO_2)	Proton Exchange membrane electrolysis water splitting
Experimental proof-of-concept	BECCS power Dense inorganic membranes Hydrate-based capture Post-combustion ionic liquids Pre-combustion low-T separation	Photoelectrochemical water-splitting
System prototype demonstrated in the operational environment	BECCS industry Cryogenic (solid CO_2) DAC (adsorbents and absorbents) Fuel cell capture Oxy-combustion coal power plant Polymeric membranes (NG industry) Post-combustion adsorption Pre-combustion IGCC CCS	
Technology validated in lab		Thermochemical water-splitting
Basic principles observed		Natural free-state geological occurrence
Technology concept formulated		

expenses. The cost per ton of captured CO_2 can vary widely, ranging from \$15 to \$342, depending on the CO_2 concentration in the emission stream [100]. Higher CO_2 concentrations typically result in lower capture costs, which is advantageous for industries like natural gas processing, chemical production, and hydrogen production via steam methane reforming [100].

Within the carbon capture, utilization, and storage (CCUS) value chain, capture costs are the highest, followed by expenses for CO_2 compression, dehydration, and transportation, typically via pipelines. On the other hand, costs for CO_2 injection and monitoring, measuring, and verification (MMV) of storage are generally <10 % of the total costs [60].

Oil and gas companies have begun adopting various carbon capture technologies. Notably, Oxy is constructing the world's largest DAC facility (DAC-1) in the Permian Basin, which is expected to be operational by early 2024. This facility will capture up to 1 million tons of CO2 annually with a purity of 99 % and will use this CO_2 for enhanced oil recovery (EOR). Oxy also plans to develop 70 additional DAC facilities by 2035, each with a capture capacity of up to 1 million tons per year [87].

Shell has been testing different carbon capture technologies and has shifted from liquid solvents to solid sorbents, which are 40 % cheaper. By 2024, Shell aims to scale up its solid sorbent technology to handle 150 tons per day, with the goal of eventually reaching 1000–2000 tons per day in commercial plants. This technology can capture over 90 % of CO_2 from post-combustion flue gases with 95 % purity [60].

Baker Hughes offers three carbon capture solutions: the chilled ammonia process (CAP), the mixed salt process (MSP), and compact carbon capture (CCC). CAP, a post-combustion technology with a technology readiness level (TRL) of 7, uses ammonia to capture CO_2 from low-pressure flue gases, while MSP uses a non-amine solvent for improved energy efficiency and reduced water usage. The CCC technology employs rotating packed beds, which are smaller, modular, and more cost-effective compared to conventional amine systems. This technology can capture 250–500 tons of CO_2 per day with 99 % purity [80].

1.5. Production of liquid e-fuels

The catalytic reduction of CO_2 to generate high-value liquid fuels represents a critical pathway toward achieving carbon-neutral energy solutions. This process plays a significant role in minimizing atmospheric CO_2 levels. By reacting CO_2 with hydrogen (H_2), various low-carbon fuels can be synthesized, ranging from methane and ethane (a precursor to ethylene, commonly used in plastic manufacturing) to propane (widely used for heating and cooking purposes). Additionally, commercially valuable liquid e-fuels such as methanol and synthetic aviation fuel (SAF) can be produced. Depending on the catalyst's effectiveness, CO_2 conversion to liquid e-fuels may follow either a single-step or a multi-step approach. In a single-step method, CO_2 is directly transformed into liquid fuel, while in a two-step process, the first reaction—known as the reverse water-gas shift (RWGS)—converts CO_2/H_2 into CO/H_2O. This is followed by a secondary reaction, where CO and H_2 combine to form the desired liquid fuel [80].

Catalyst performance, particularly in terms of selectivity and reaction rates, often limits the efficiency of CO_2 conversion to liquid fuels. Reactor design that ensures optimal operational conditions, alongside the selection of appropriate catalysts, is essential to the success of producing high-value e-fuels from CO_2/H_2 mixtures. In subsequent sections, the specific reactions, catalysts, and methods for producing e-methanol and SAF are explored.

(a) e-Methanol Production

Although the majority of methanol is traditionally produced through syngas (a mixture of CO and H_2), it is also possible to synthesize methanol renewably via the direct hydrogenation of CO_2. The CO_2 and H_2 reactants are typically pressurized to around 25 bar before entering a high-temperature, high-pressure reactor. If the initial pressures of CO_2 and H_2 are insufficient, they are compressed before feeding into the reactor. After methanol formation, unreacted gases are recycled through a compressor and reintroduced into the reactor, along with fresh reactants [15,54]. The exothermic nature of methanol synthesis provides heat for the endothermic RWGS (Reverse water gas shift) reaction. A key difference between conventional and renewable methanol production is the substantial water content in the output stream of renewable methanol production (up to 30–40 % by mass), which adversely impacts catalyst performance and longevity. Several critical elements influence methanol synthesis. For example, composition of the syngas feed (especially if the H_2 used is impure). Reactor designs that manage the

Table 2
Summary of technologies for production of hydrogen ([4,41,43,46,62,73,82,93,102,121,105,106,122,25,39,47,81]).

Technology	Description	Advantages	Disadvantages	TRL (max. 9)	Cost [$ per kg H_2]
Natural free-state occurrence	Naturally occurring free-state H_2 found in geological media.	Can be extracted using existing oil and gas drilling technology.	Its geology of occurrence is not well-understood	1	Most economical
From Water-splitting					
Photoelectrochemical (PEC) process	Produces H_2 by splitting water through semiconductor immersed in a water-based electrolyte that uses visible light as the input energy	Low operating temperatures and cost-effective materials (thin-film, particle semiconductor). Can utilize an unlimited source of solar light	Very low solar-to-H_2 conversion efficiency (<3 %). Low current density due to reduced area of electrolysis in solar cell	2–3	5.70
Thermochemical process	Produces H_2 by splitting water through a series of high- temperature (800–900 °C) chemical reactions by using heat as the input energy. A single step conversion of water to H_2 through direct thermolysis is possible, but not practical as it requires extremely high temperature (>2500 °C)	Suitable for large- scale production capacity that is larger than the scale of H_2 refueling station. Can utilize sunlight and/or heat from nuclear waste	Requires additional H_2 distribution network due to its large-scale production capacity. Commercial viability is currently challenging	2–4	3.70
From Water-splitting - *Electrolysis*					
Solid-oxide	Electrolysis process converts water directly into H_2 and oxygen (without any partial reactions with other chemicals/compounds) by using electricity as an input energy. Primary electrolysis components consist of an anode and a cathode separated by an electrolyte.	Can leverage both heat and electrical energy	Require high temperature (>700- 800 °C). Slower start-up time	5	2.30 (with $0.037 per kWh as electricity cost)
Polymer electrolyte [or proton exchange] membrane (PEM)		Can operate at high current densities. Perform better with fluctuating input currents. Integrate better with variable power generation, such as wind and solar. Faster response time	Expensive materials that add to the cost. Scale-up to the MW scale is a challenge.	6–8	2.30 (with $0.037 per kWh as electricity cost)
Alkaline		Mature technology. The first water splitting technology to be developed. Relatively low cost	Corrosive liquid electrolyte. Perform poorly with fluctuating power sources, because of a slow response (startup) time.	9	2.30 (with $0.037 per kWh as the electricity cost)
From biomass and waste-stream					
Dark fermentation	Wet biomass. Uses anaerobic bacteria under dark conditions	Relatively simple technology. Waste recycling. CO_2-neutral process.	Low yield of H_2 relative to reactor volume.	4–5 (3–5 with CCS)	2.57
Gasification	Dry biomass. Uses a controlled amount of oxygen and/or steam. No bacteria required.	Relatively simple technology. Waste recycling. CO_2-neutral process.	Pre-treatment cost. Fluctuating H_2 yields because of feedstock impurities. Co-produces tar	5–6 (3–5 with CCS)	1.77–2.05
In situ combustion of hydrocarbon reservoirs	Steam/air/oxygen injection in fossil fuel-bearing reservoirs	Unwanted gases are not produced via downhole purification. Low-cost production	Complex in situ combustion that is difficult to control and predict	3–5	<2
Photo fermentation	Wet biomass. Uses anaerobic bacteria and light	Relatively simple technology. Waste recycling. CO_2-neutral process	Low yield of H_2 relative to reactor volume	4–5 (3–5 with CCS)	2.83
Pyrolysis of methane	Uses a catalyst to crack. methane at high temperature in the absence of oxygen	No CO_2 emission. Produces solid carbon	Co-produces tar that can plug the reactor	3–5	1.59–1.70
From fossil fuels					
Plasma reforming	Similar to SR, but uses high temperature electric heat from plasma devices instead of steam	Does not require a catalyst. Reduced reactor size and weight	High electricity requirements. Produces CO_2	5–6	<2.08
Partial oxidation (POX)	Steam created by combustion with partial use of oxygen. No catalyst used. Exothermic	Faster start-up times. and relative compactness. No catalyst required	Produces CO_2	9	1.48 (with CCS)
Coal gasification	Steam and oxygen are used for combustion and reacted with coal	Simpler emission control over conventional combustion	Produces CO_2 and other pollutants	9 (6–7 with CCS)	1.34 (without CCS)- 1.63 (with CCS)
Steam reforming (SR)	The steam created by combustion with air is reacted with the feedstock and catalyst. Endothermic	Mature technology and easier to scale up	Produces CO_2	9 (7–8 with CCS)	2.08 (without CCS)- 2.27 (with CCS)
Auto-thermal reforming (ATR)	Combination of steam reforming and partial oxidation	Faster response times. Simpler and cheaper than SR. Compact design relative to other fossil fuel-based methods	Produces CO_2 Requires pure oxygen or air separation unit. Limited commercial experience	9 (7–8 with CCS)	1.48 (with CCS)

heat generated by the exothermic reaction, including gas-cooled and steam-raising configurations (axial, radial, and axial–radial). Commercially, three reactor designs are employed based on heat transfer mechanisms: (i) quench converter (direct cooling via feed gas injection), (ii) tube-cooled converter (counter-current gas exchange), and (iii) steam-raising converter (isothermal bed temperatures). Among these, the tube-cooled converter (TCC) achieves the highest methanol production and carbon efficiency per reactor volume, while the

Table 3
Carbon Capture Technologies [26,27,31,52,53,55,67,90,92,115–117].

			Characteristics						
			Source of CO_2 emission	Capture mechanism	CO_2, capturing agents	Outputs	Advantages	Disadvantages	Major industrial sectors
		Pre-combustion	Syngas coming from gasification units prior to combustion	Sorption with pressure and/or temperature swing	Solvents and membranes	CO_2, and H_2	High capture efficiency	Less mature technology	Power and industrial gases
Post-combustion		**Traditional method**	Flue gas due to combustion with air and fuel	Sorption with pressure and/or temperature swing	Solvents, membranes, and adsorbents	CO_2, and N,	Most mature technology	Lower capture efficiency	Power and cement
	Specialized methods	**Cryogenic**	Flue gas due to combustion with air and fuel	Direct phase change from gas to liquid/solid	Cryogenic cooling with liquid solvents	CO_2, N_2, SOX, NOx, and Hg	A high concentration of CO_2, is captured	Relatively high CAPEX	Power and cement
		Oxyfuel combustion	Flue gas due to combustion with oxygen and fuel. O, is supplied externally from an air separation unit	Sorption with pressure and/or temperature swing	Solvents and membranes	CO_2, and steam	Leads to a high concentration of CO_2, in flue stream, which is easier to capture	Relatively high CAPEX	Power and steel
		Chemical looping	Flue gas due to combustion with oxygen and fuel. O, is extracted internally from the solid-state oxygen carrier through reduction-oxidation reactions	Sorption with pressure and/or temperature swing	Solvents and membranes	CO_2, and O_2	Cost-effective option to oxycombustion, but with similar benefits	Less mature technology	Power and steel
		Fuel cells	Flue gas due to combustion with air (and/or oxygen) and fuel	FCs pump CO_2 through the electrolyte to separate CO_2, via selective ionic transport	Electrochemical system	CO_2, water, and some H	Very high capture efficiency. Cheaper. Can also utilize CO_2 as the working fluid	Less mature technology	Power and industrial gases
		DAC	Air. No combustion	Membrane separation and/or sorption	Adsorbents and membranes	CO_2, and air	Can capture CO_2 anywhere on the earth. without the need for point-source emission	Relatively high CAPEX	Greenhouse and carbonated beverages

quench-type reactor contains the largest catalyst volume [75]. Producing one kilogram of methanol requires approximately 0.189 kg of H2 and 1.373 kg of CO_2 under specific conditions. However, other studies have indicated that the CO_2 consumption rate is closer to 1.4 kg of CO_2 per kg of e-methanol. Methanol synthesis involves balancing the exothermic hydrogenation reaction with the endothermic RWGS reaction. At higher temperatures, the yield of methanol decreases due to increased activation of CO_2 into undesired products like CO and H_2O [75].

Historically, catalysts used for methanol production, such as Cu, Zn, and Al, are abundant but suffer from poor water tolerance. Excessive water production in e-methanol synthesis reduces the activity and lifespan of these catalysts. To enhance CO_2 hydrogenation for e-methanol production, more robust catalysts with higher water stability and activity are required [66]. A variety of catalysts have been investigated, ranging from transition metals and metal oxides to precious metals and main group elements. The cost-effectiveness of e-methanol production depends on factors such as H_2 production costs, CO_2 feedstock price, and carbon credits. Cost reductions are achievable as production scales up, with significant savings seen at capacities exceeding 4400 tons per day [74].

(a) e-Kerosene and Sustainable Aviation Fuel (SAF) production

Aviation contributes around 2–3 % of global carbon emissions, and these emissions are rising steadily as air travel increases. One approach to reducing emissions in this sector is through the use of Sustainable Aviation Fuel (SAF), which refers to synthetic aviation fuels produced using clean hydrogen and captured carbon dioxide. In addition to being carbon-neutral, SAF can be blended with conventional fossil-based aviation fuels without requiring modifications to existing infrastructure or aircraft systems. The first commercial flight utilizing SAF took place on February 8, 2021, aboard a Boeing 737 from Amsterdam to Madrid, using 500 liters of e-kerosene mixed with regular aviation fuel [91].

SAF can be synthesized using the Fischer-Tropsch (FT) process, a catalytic method that converts CO_2/H_2 or syngas (CO/H_2) into liquid hydrocarbons, such as e-diesel or e-kerosene, with the desired carbon chain length depending on operating conditions. The typical composition of SAF includes n-alkanes, isoalkanes, and cycloalkanes, with carbon chain lengths generally between C_8 and C_{18}. The SAF production process comprises six main stages [6]: (i) compression of H_2 and CO_2, (ii) the reverse water gas shift (RWGS) reactor, (iii) the FT synthesis reactor, (iv) hydroprocessing, (v) power generation, and (vi) utility operations. In the first step, H_2 and CO_2 are compressed to approximately 25 bar before entering the RWGS reactor, where CO is generated. This CO is subsequently fed into the FT synthesis reactor, where it reacts with hydrogen to produce liquid fuels. The FT reaction is exothermic, producing heat that is utilized in the RWGS reactor. Efficient heat removal is critical in the FT reactor to ensure optimal performance. Various reactor designs are used for FT synthesis, each with distinct heat transfer mechanisms. These include circulating fluidized bed reactors, fluidized bed reactors, tubular fixed bed reactors, and slurry phase reactors. To produce 1 kg of SAF via the FT process, approximately 1.36 kg of H_2 and 14.55 kg of CO_2 are required [120]. The catalysts typically used for FT synthesis are cobalt or iron-based, while barium cerium zirconate serves as the catalyst for the RWGS reaction. The FT process has been estimated to utilize around 2.6 tons of CO_2 for every ton of fuel produced, based on traditional CO_2 and methane reforming. In the FT process, the RWGS reaction generates CO from captured CO2, which is essential for the primary FT reaction. The composition of the resultant hydrocarbons, particularly the chain length of the products, is influenced by the catalysts and syngas composition. SAF typically consists of hydrocarbons with carbon chains ranging from 17 to 32 atoms. The FT process can produce other non-diesel hydrocarbons, which are often upgraded via hydrocracking to diesel. While commercial FT processes use Co- and

Tabla 4
The challenges and opportunities associated with e-fuel production in relation to the goals of the 2030 Agenda.

Challenges	Opportunities	Relevant SDGs
High Production Costs	Economies of Scale	SDG 7: Affordable and Clean Energy
- Significant capital investment for electrolyzers and infrastructure.	- Larger production facilities can reduce unit costs through mass production.	SDG 9: Industry, Innovation, and Infrastructure
- Operational expenses for maintaining reaction conditions.	- Improved economies of scale can enhance profitability and attract investments.	SDG 12: Responsible Consumption and Production
Energy-Intensive Processes	Technological Advancements	SDG 7: Affordable and Clean Energy
- High electricity demands for water electrolysis and hydrocarbon synthesis.	- Research in more efficient electrolyzers and catalysts can significantly reduce energy consumption.	SDG 9: Industry, Innovation, and Infrastructure
- Increased energy consumption due to high temperatures and pressures.	- Development of novel CO_2 capture technologies can enhance sustainability.	SDG 7: Affordable and Clean Energy
Need for Technological Advancements	Innovation in Materials and Catalysts	SDG 9: Industry, Innovation, and Infrastructure
- Current technologies are still in developmental phases, limiting scalability.	- Innovations in materials science and catalytic chemistry can improve efficiency and lower costs.	SDG 12: Responsible Consumption and Production
- Critical need for improved CO_2 capture methods to ensure carbon-neutrality.	- Breakthroughs in reactor design and process integration can enhance overall system performance.	SDG 7: Affordable and Clean Energy
Operational Flexibility	Utilization of Renewable Energy	SDG 7: Affordable and Clean Energy
- Need for flexible systems to adapt to fluctuating renewable energy sources.	- E-fuels can provide a stable energy supply, facilitating the integration of intermittent renewable energy.	SDG 13: Climate Action
- Trade-offs between energy storage and operational flexibility.	- The ability to store energy as e-fuels can enhance grid stability and resilience.	SDG 9: Industry, Innovation, and Infrastructure
Lack of Concrete Guidance for Stakeholders	Clear Recommendations for Adoption	SDG 9: Industry, Innovation, and Infrastructure
- Insufficient advice on the most promising e-fuel types and electrolysis technologies.	- Providing concrete advice on e-fuels and electrolysis technologies can guide investment decisions.	SDG 17: Partnerships for the Goals
- Need for justification of technology choices based on operational flexibility and cost efficiency.	- Identifying promising technologies can facilitate targeted research and development funding.	SDG 9: Industry, Innovation, and Infrastructure

Fe-based catalysts, advanced catalysts such as nickel and ruthenium-based materials have shown greater catalytic activity, although they are not yet widely implemented in industrial applications. Recently, research has focused on improving FT catalysis, such as using Fe–Mn–K catalysts for higher conversion rates and selectivity towards longer hydrocarbon chains. The minimum fuel selling price of SAF depends on various factors, including the cost of hydrogen, CO_2 feedstock, and the credits from CO_2 capture. The MFSP typically ranges from \$4.30 to \$6.78 per gallon, influenced by the price of H_2 (between \$0.8 and \$5 per kg) and CO_2 (ranging from \$0 to \$76.2 per ton) [87]. The cost of CO_2 can significantly affect production costs, particularly if it is sourced from industries such as ethanol, ethylene oxide, or ammonia production. Additionally, factors such as the hydrogen recycling ratio, CO conversion efficiency, and CO_2 recycling also play crucial roles in determining the overall costs of SAF production [64].

(a) e-LNG (Electro-Liquefied Natural Gas) production

e-LNG, also known as electro-liquefied natural gas, is primarily composed of methane (CH_4) and is produced through the chemical conversion of green hydrogen (H_2) and captured carbon dioxide (CO_2) via the Sabatier reaction. The resulting methane is then liquefied to create a product suitable for use in transportation, offering a cleaner, more sustainable alternative to conventional liquefied natural gas (LNG). e-LNG can be integrated into existing natural gas infrastructure, allowing for its use in marine, road, and rail transport with minimal modifications to engines or storage systems [99]. The production of e-LNG begins with the generation of green hydrogen through water electrolysis, powered by renewable energy sources such as wind, solar, or hydropower. This hydrogen is then reacted with captured CO_2 in the Sabatier process, a catalytically driven reaction that synthesizes methane and water. The overall reaction is highly exothermic, releasing heat that can be recovered and utilized elsewhere in the process to improve energy efficiency. The produced methane is then subjected to a liquefaction process, where it is cooled to cryogenic temperatures (approximately −162 °C) to form liquefied natural gas (LNG). This liquefied methane is more energy-dense, making it suitable for storage and transport in the same manner as conventional LNG. The overall e-LNG production process can be divided into several key stages: (i) H2 generation via electrolysis, (ii) CO2 capture and compression, (iii) the Sabatier reactor for methane synthesis, (iv) heat recovery and management, (v) methane liquefaction, and (vi) utility operations for cooling and energy integration. Efficient heat removal and recovery are critical in the Sabatier reaction, given its highly exothermic nature. In the Sabatier process, hydrogen and carbon dioxide serve as the primary feedstocks, and their consumption rates are dictated by the stoichiometry of the reaction. For every kilogram of methane produced, approximately 0.5 kg of hydrogen and 2.75 kg of carbon dioxide are consumed [87]. The efficiency of the process depends on the purity of the feed gases, as impurities can negatively affect catalyst performance and methane yield. The choice of catalyst is critical for optimizing methane production. Common catalysts for the Sabatier reaction include nickel-based materials, which offer high activity and selectivity towards methane. Research is ongoing to develop more robust catalysts that can withstand the high temperatures and pressures involved, while improving conversion efficiency and reducing by-product formation. Additionally, advances in catalyst design, such as the use of doped metals or structured supports, aim to enhance the durability and effectiveness of the Sabatier reactor. The Sabatier reaction, central to e-LNG production, involves the reduction of carbon dioxide with hydrogen to produce methane and water. The reaction is exothermic, with heat generation influencing the reactor's temperature control and energy balance. Proper management of the reaction's thermal output is essential for maintaining optimal operating conditions and maximizing methane yield [101]. The selectivity of the methane produced and the reaction kinetics depend on the operating temperature, pressure, and catalyst used. Nickel-based catalysts are the most widely utilized in industrial applications due to their high activity for CO_2 methanation and cost-effectiveness [74]. However, research is underway to improve catalytic stability and reduce the deactivation caused by carbon deposition on the catalyst surface. Alternative catalysts, such as ruthenium or cobalt-based materials, have also shown promise in increasing methane yields and extending catalyst life under varying operational conditions. In terms of reactor design, different configurations such as fixed-bed, fluidized-bed, or microchannel reactors are employed, each offering distinct advantages in terms of heat management and methane productivity [80]. Fluidized-bed reactors, for instance, provide superior heat transfer capabilities, while fixed-bed reactors are simpler to operate and maintain. The economic feasibility of e-LNG production is heavily influenced by the cost of hydrogen, carbon dioxide capture, and the energy required for methane liquefaction. Hydrogen, generated via water electrolysis, represents a significant portion of the production cost, with its price varying depending on the availability and cost of renewable energy. The cost of CO_2 capture also plays a critical role, as it is dependent on the source and the technology employed for its collection and purification [77].

The minimum selling price of e-LNG fluctuates based on several factors, including the scale of production, energy prices, and the credit from CO_2 emissions reduction. With hydrogen prices ranging between \$1.5 to \$6 per kilogram and CO_2 capture costs from \$20 to \$100 per ton, the production costs of e-LNG can vary significantly. Furthermore, integration of energy recovery systems, optimization of reactor efficiencies, and advancements in CO_2 capture technologies could reduce overall production costs, making e-LNG a more economically competitive solution compared to conventional LNG [111].

1.6. Challenges in E-Fuels production

The transition to sustainable energy sources is critical in addressing global climate change and achieving carbon neutrality. E-fuels, or electro-fuels, have emerged as a promising alternative to conventional fossil fuels, offering a pathway to decarbonize sectors that are challenging to electrify, such as aviation, maritime transport, and heavy industry. However, the production of e-fuels faces substantial economic and technological hurdles that must be addressed to unlock their full potential [37].

1.7. High production costs

The production of e-fuels faces significant economic hurdles, primarily driven by the high electricity demands for water electrolysis and the energy-intensive synthesis processes. The capital investment required for state-of-the-art electrolyzers, reactors, and associated infrastructure, alongside operational expenses to maintain ideal reaction conditions, further compounds the cost. Achieving cost parity with conventional fossil fuels will require substantial cost reductions through improved economies of scale, enhanced efficiency, and technological breakthroughs [78]. Additionally, a critical element that impacts production costs, often overlooked, is operational flexibility. While the flexibility of modular systems for scaling up or down a design is beneficial, it is the operational flexibility—the ability to adjust production rates in real-time based on fluctuating renewable energy availability—that will likely play a central role in cost reduction. As renewable energy sources like wind and solar are inherently variable, balancing this intermittency with effective energy storage (such as batteries or hydrogen) and operational adaptability will become key to ensuring continuous production and minimizing idle times. Studies indicate that improving this operational flexibility could lead to cost reductions of 15–20 %, especially in regions with high renewable energy penetration, as it reduces reliance on external energy sources during periods of low generation [34].

1.8. Energy-intensive processes

Both the electrolysis of water to produce hydrogen and the subsequent hydrocarbon synthesis processes require large energy inputs. For instance, electrolysis consumes around 50–55 kWh per kilogram of hydrogen produced. This process alone represents a significant energy burden, particularly when compared to the lower energy requirements of conventional fuel production. Current electrolyzer efficiencies range between 65 % and 75 %, but improving these values to 80 % or higher will be essential to making e-fuel production more energy-efficient and cost-effective [46]. To this end, solid oxide electrolyzers (SOECs), which can achieve efficiencies of up to 90 % when operating at high temperatures (800–1000 °C), are being considered as a viable option for future deployment. However, SOECs face challenges in terms of durability and cost, with degradation rates that need to be reduced for long-term viability [46].

The subsequent hydrocarbon synthesis processes, such as Fischer-Tropsch or methanol synthesis, further compound the energy demand. These processes require high temperatures (typically 200–300 °C) and pressures (10–30 bar), both of which increase the overall energy footprint [37]. Technological advancements aimed at reducing this energy consumption—such as improving catalytic efficiency or integrating waste heat recovery systems—will be critical for reducing production costs and making e-fuels a more viable alternative. For instance, waste heat from the synthesis process could be repurposed to preheat the reactants for electrolysis, thereby improving overall energy efficiency [47].

1.9. Need for technological advancements

Current technologies for e-fuels production remain in a developmental phase, necessitating improvements across several key areas. More efficient electrolyzers, advanced catalysts for hydrocarbon synthesis, and improved CO_2 capture methods are critical to enhancing both the economic viability and environmental sustainability of e-fuels. In the context of operational flexibility, one of the most promising developments is in proton exchange membrane (PEM) electrolyzers, which are particularly well-suited to the fluctuating output of renewable energy sources. PEM electrolyzers can adjust quickly to changes in power input and can operate efficiently at partial loads, down to 10–20 % of their rated capacity, without significant efficiency losses [62]. This adaptability is essential when integrating renewable energy, where power supply is not constant. Although PEM electrolyzers are currently more expensive than traditional alkaline electrolyzers—capital costs range from \$1000 to \$1500/kW for PEM systems compared to \$500 to \$1000/kW for alkaline systems—their potential to lower operational costs by maximizing renewable energy utilization justifies the investment in the long term [37].

Another crucial area for technological improvement lies in CO_2 capture and utilization (CCU). The reliance of e-fuels on captured CO_2 to achieve carbon neutrality means that advancements in CCU technologies will directly impact the viability of these fuels. Current CO_2 capture technologies, such as amine-based solvents, are energy-intensive, adding further costs to the e-fuel production process. Emerging technologies, such as solid sorbents and metal-organic frameworks (MOFs), offer promising alternatives with lower energy requirements for CO_2 capture. For example, MOFs have demonstrated the ability to selectively capture CO_2 at lower pressures and temperatures, potentially reducing the energy needed for CO_2 capture by 20–30 % [41]. The integration of such technologies into the e-fuel production chain could significantly improve overall efficiency and lower costs [102].

1.10. Recommendations and concrete advice

Most Promising E-Fuel: Among the various e-fuels under consideration, e-methanol currently stands out as the most promising in terms of both production efficiency and scalability. E-methanol benefits from a relatively simple synthesis process compared to other e-fuels, such as e-diesel or e-kerosene, which require more complex multi-step synthesis pathways. In terms of production efficiency, e-methanol can achieve overall energy conversion efficiencies of around 50–60 %, compared to 40–45 % for e-diesel [37]. Moreover, e-methanol's compatibility with existing infrastructure—such as pipelines, storage facilities, and internal combustion engines—makes it a favorable option for near-term implementation, particularly in the maritime and industrial sectors.

Most Promising Electrolysis Technology: In terms of electrolysis technologies, PEM electrolyzers represent the most promising option for integration with fluctuating renewable energy sources. Their ability to respond dynamically to changes in power input and operate efficiently at low loads makes them well-suited for regions with high levels of wind or solar energy [4]. While the capital costs of PEM systems are currently higher than those of alkaline electrolyzers, PEM's ability to operate more flexibly could lower operational costs by reducing the need for additional energy storage. Given that energy storage costs can account for up to 20–30 % of the overall cost of e-fuel production, PEM's operational flexibility offers a pathway to significant cost reductions over the long term [37].

Balancing Operational Flexibility and Energy Storage: One of the critical cost-saving opportunities in e-fuel production lies in finding the optimal balance between operational flexibility and energy storage. Energy storage systems, such as batteries or hydrogen storage, add significant costs to the production process, and their sizing must be carefully balanced with the operational flexibility of the electrolysis and synthesis units. A more flexible production system, capable of ramping up or down in response to energy availability, can reduce the reliance on expensive storage solutions. For example, reducing energy storage capacity by 10–15 % could lower overall production costs by 8–12 %, provided the system can maintain high operational flexibility [37]. In conclusion, by addressing the operational flexibility of e-fuel production systems, optimizing electrolysis technologies for renewable energy integration, and offering concrete recommendations on the most promising e-fuels and technologies, the industry can move toward more economically viable and scalable solutions. These advancements will be crucial in ensuring that e-fuels can play a significant role in decarbonizing sectors such as aviation, shipping, and heavy industry, aligning with global sustainability goals [122].

The application of e-fuels in the transportation sector: It topic presents various opportunities and challenges as the world strives to achieve the objectives outlined in the 2030 Agenda. Hydrogen is currently one of the more expensive options for truck transport; however, it could become a viable alternative if solutions are developed to address high distribution costs, such as utilizing pipeline distribution, and if vehicle costs decrease through innovations in fuel cell technology or economies of scale. Significant progress in these areas is not expected until after 2030. In contrast, e-methanol, e-diesel, and e-LNG appear to be the most promising options for truck transport, inland shipping, and deep-sea shipping. The estimated cost differences between hydrogen and e-ammonia are minimal, likely falling within the uncertainty range of existing calculations [112]. Thus, while hydrogen shows potential, e-fuels may offer more immediate practical solutions. For short-sea mobility scenarios, hydrogen emerges as the most economically attractive option, especially for short-distance ferries and inland shipping routes. The costs associated with hydrogen and e-fuels are highly sensitive to fluctuations in CO_2 pricing (for e-LNG, e-methanol, and e-diesel) and electricity costs across all assessed e-fuels. As carbon emissions are produced during the combustion of carbon-based fuels, it is crucial that CO_2 utilized in the production of e-fuels be captured from a circular source—such as through direct air capture—to achieve a nearly net-zero emission profile [37]. This requirement can lead to elevated CO_2 costs, significantly influencing the economic competitiveness of various fuels. In scenarios where electricity and CO_2 costs are high, hydrogen often becomes the most economical option across most transport modes, except for deep-sea applications where it is not applicable. Following hydrogen, e-ammonia remains a consideration, though its safety for road transport is currently questioned. An analysis of key performance indicators (KPIs) in transportation yields several conclusions. For trucking, hydrogen is applicable primarily for short-distance transport, becoming attractive when electricity and CO_2 costs are high or when infrastructure and vehicle costs have significantly decreased. In most other cases, e-methanol, e-diesel, and e-LNG are preferred options, with e-ammonia deemed unsafe for road transport at present (IEA, 2020). Regarding shipping, the cost differences among e-fuels are minimal. Hydrogen is beneficial in applicable situations, especially when CO_2 costs are elevated. E-ammonia also offers promise under high CO_2 cost conditions, particularly for deep-sea shipping, while e-methanol, e-diesel, and e-LNG are advantageous when CO_2 costs are lower. Lastly, in aviation, e-kerosene is recognized as the sole viable e-fuel option, underscoring the necessity for targeted innovations in this sector [50]. In conclusion, although green hydrogen possesses the lowest production costs per gigajoule (GJ), its overall value chain expenses are higher than those of most e-fuels under base case conditions, except in short-sea shipping. Given the highly variable outcomes of cost comparisons influenced by electricity and CO_2 pricing, no single fuel emerges as a definitive winner, necessitating further exploration and development in the realm of e-fuels to meet the transportation sector's sustainability goals.

The Table 4 highlights the interconnectedness of the challenges and opportunities in e-fuel production with specific SDGs from the 2030 Agenda. Addressing these challenges through innovative strategies is essential for advancing towards the achievement of sustainable energy goals and contributing to a more resilient and sustainable global energy landscape [88,89].

2. Challenges in process intensification for e-fuels production

Process intensification (PI) represents a transformative approach aimed at enhancing the efficiency, sustainability, and compactness of chemical processes. This methodology is particularly crucial in the realm of e-fuels production, where it addresses several pressing challenges inherent to the industry. By leveraging innovative materials, advanced reactor designs, and optimized process configurations, PI seeks to reduce energy consumption, elevate reaction rates, and maximize resource utilization [22]. Given the urgent need to meet global sustainability goals and the specific targets outlined in the 2030 Agenda for Sustainable Development, the strategic implementation of PI can play a pivotal role in the industrial-scale adoption of e-fuels [30].

a) Enhanced efficiency

The primary aim of PI in e-fuels production is to significantly enhance process efficiency. This encompasses optimizing both electrolyzers and synthesis reactors, which are vital components of the production process.

2.1. Electrolyzer efficiency

The efficiency of water electrolysis, a process that converts renewable electricity into hydrogen, is critically influenced by the materials utilized within electrolyzers. Employing high-performance materials, such as advanced electrode coatings and cutting-edge membrane technologies, can enhance electrolysis efficiency and diminish energy consumption. For instance, utilizing conductive and durable materials helps in lowering overpotentials and increasing operational stability. Innovations like proton exchange membranes (PEMs) and solid oxide electrolyzers (SOEs) are at the forefront of improving the efficiency and durability of electrolyzers, thereby enhancing the viability of these technologies at an industrial scale [33]. In a comparative numerical analysis, the efficiency of state-of-the-art PEM electrolyzers can reach up to 80–90 %, while traditional alkaline electrolyzers typically operate in the range of 60–70 % efficiency. Such differences underscore the importance of technological advancements in driving efficiency improvements [9].

Strategy in Use: The adoption of advanced membrane technology in PEM electrolyzers, focusing on material science advancements to minimize energy losses, illustrates the direct application of PI strategies in this sector.

2.2. Synthesis reactor optimization

Similarly, advancements in reactor design are vital for improving hydrocarbon synthesis from hydrogen and CO_2. Innovative concepts, such as structured catalysts and microreactors, are instrumental in enhancing heat and mass transfer, which in turn leads to more efficient reaction kinetics and reduced energy requirements. The integration of these novel reactor designs can significantly improve overall process performance. Furthermore, techniques such as dynamic reactor operation and advanced process intensification methods—including membrane reactors and microwave-assisted synthesis—can further boost efficiency and selectivity in chemical processes [79]. For instance, a recent study showed that microreactors could enhance the overall yield of Fischer-Tropsch synthesis by approximately 20 % compared to traditional reactor designs, due to improved heat management and reaction control [79].

Strategy in Use: The use of microreactors for Fischer-Tropsch synthesis exemplifies a strategy where PI is applied to enhance reaction control and increase yield through improved heat and mass transfer.

a) Cost Reduction

Reducing costs is essential for making e-fuels production economically viable. PI contributes to this objective through enhanced process efficiency and reduced energy consumption.

2.3. Materials and reactor engineering

Advances in materials science and reactor engineering are central to achieving cost reductions. The development of cost-effective, durable catalysts decreases the frequency of replacements and thus lowers operational expenses. Enhanced reactor designs that minimize energy losses and optimize resource utilization contribute to lower capital and operational expenditures. The use of long-lasting materials not only decreases costs but also extends the lifespan and productivity of production units [35]. For example, the transition from noble metal catalysts to more abundant materials like nickel and copper in catalytic processes has led to a reduction in catalyst costs by over 50 %, significantly impacting the overall production cost of e-fuels [89].

Strategy in Use: The transition to cost-effective catalyst materials illustrates a PI strategy focused on material efficiency, ensuring lower operational costs and greater economic feasibility in e-fuels production.

2.4. Process integration

Effective process integration is another critical pathway for reducing costs. Streamlining production stages and incorporating energy recovery systems can help lower overall production costs. For instance, integrating waste heat recovery systems into production processes can significantly reduce energy needs and operational costs. The implementation of integrated process designs—where multiple reactions and separations occur simultaneously within a single unit—can yield substantial savings by minimizing the number of individual processing steps and associated energy inputs [106]. A case study of a leading e-fuels producer, Neste, demonstrated that their integrated approach to waste heat recovery could lead to a reduction in energy costs by up to 30 %, reinforcing the importance of process integration in achieving cost-effectiveness [63].

Strategy in Use: Neste's implementation of integrated process designs showcases how process integration strategies in PI can lead to substantial energy and cost savings, promoting overall economic viability.

a) Environmental Sustainability

In addition to economic benefits, PI plays a crucial role in enhancing the environmental sustainability of e-fuels production. By optimizing processes and adopting advanced technologies, the environmental impact of production can be mitigated.

2.5. Waste heat recovery

The integration of waste heat recovery systems, such as combined heat and power (CHP) systems, enhances the overall sustainability of e-fuels production. Capturing and reusing waste heat from various production stages improves energy efficiency and reduces greenhouse gas emissions. Additionally, utilizing waste heat in other industrial processes or for district heating can significantly bolster the sustainability profile of e-fuels [57]. A comparative analysis revealed that facilities utilizing CHP systems can achieve overall energy efficiencies of up to 90 %, compared to traditional systems that typically operate at around 35–45 % efficiency [24]

Strategy in Use: The incorporation of CHP systems is a classic PI strategy that enhances energy recovery and reduces emissions, directly contributing to improved environmental sustainability.

2.6. CO_2 capture and utilization

Advancements in CO_2 capture and utilization technologies are critical for minimizing the environmental footprint of e-fuels production. Developing efficient and cost-effective capture methods ensures that CO_2 used in synthesis processes is effectively captured and utilized, minimizing overall emissions. Technologies such as direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS) can supply high-purity CO_2 for synthesis, enhancing the carbon neutrality of e-fuels [59]. Notably, Carbon Capture Market overview [13] has demonstrated the potential to capture CO_2 at a cost of around $100 per ton, enabling a sustainable feedstock for e-fuels production while supporting climate goals [107].

Strategy in Use: Application of DAC exemplifies a PI strategy focused on resource efficiency and carbon neutrality, which is essential for the sustainable production of e-fuels.

a) Scalability and Flexibility

The modular and scalable nature of PI technologies provides substantial advantages in e-fuels production, particularly in the context of fluctuating market demands and renewable energy integration.

2.7. Modular systems

Modular reactors and process units can be customized to meet specific production requirements and scaled according to demand. This flexibility allows for localized production, reducing the necessity for extensive transportation of raw materials and products. Additionally, modular systems facilitate easier upgrades and integration of new technologies as they become available, ensuring alignment with evolving market conditions.

For example, Hyzon Motors [36] has been implementing modular hydrogen production systems that can be easily scaled up or down based on regional demands for e-fuels, demonstrating the adaptability of PI technologies.

Strategy in Use: The modular hydrogen production systems at Hyzon Motors illustrate the implementation of scalable PI strategies, enabling flexibility in production to respond to market dynamics.

2.8. Scalability

Scalable PI technologies can adjust to varying production scales and energy inputs, essential for integrating renewable energy sources and accommodating fluctuations in feedstock availability. This scalability ensures that production facilities can respond dynamically to market demands and technological advancements, supporting the development of decentralized production facilities. Such decentralization promotes resilience and enhances energy infrastructure. Advancements in high-temperature electrolysis, novel CO_2 capture techniques, and innovative catalytic materials promise further enhancements in the efficiency and sustainability of e-fuels production [12]. For instance, high-temperature electrolysis utilizes heat sources to improve energy efficiency, while new CO_2 capture methods can reduce costs and enhance performance. Developments in nanomaterials and biotechnology also hold significant potential for creating more efficient and selective catalysts, thereby optimizing the chemical processes involved in e-fuel production. A numerical comparison indicates that high-temperature electrolysis can achieve efficiencies of up to 95 %, significantly surpassing traditional methods and supporting the economic viability of e-fuels [51].

Strategy in Use: The ongoing research in high-temperature electrolysis exemplifies an innovative PI strategy focused on improving process efficiency through technological advancements.

a) Research and development

Investing in research and development is essential for fostering innovation in PI technologies. Collaborative initiatives involving academia, industry, and government agencies can accelerate the development and implementation of new solutions. Such partnerships are critical for translating breakthrough research into practical, industrial-scale applications, ultimately contributing to the continuous improvement of e-fuels production technologies [17].

a) Impact on the 2030 Agenda

The application of process intensification in e-fuels production directly supports several Sustainable Development Goals (SDGs) outlined in the 2030 Agenda [89]. For example:

SDG 7 (Affordable and Clean Energy): By enhancing the efficiency and reducing the costs of e-fuels production, PI can contribute to the availability of affordable, reliable, and sustainable energy for all.

SDG 9 (Industry, Innovation, and Infrastructure): Innovations resulting from PI can lead to more sustainable industrial practices and improved infrastructure that supports the transition to renewable energy sources.

SDG 13 (Climate Action): By decreasing greenhouse gas emissions through improved energy efficiency and carbon capture technologies, PI contributes to climate mitigation efforts.

In summary, process intensification offers a robust framework for addressing the challenges of e-fuels production by enhancing efficiency, reducing costs, promoting sustainability, and fostering technological innovation. The strategic implementation of PI methodologies plays a pivotal role in advancing the production of e-fuels, aligning with the broader goals of the 2030 Agenda [61]. The continuous development and application of these strategies are essential for driving the transition to a more sustainable and resilient energy future.

3. Opportunities for process intensification

The field of e-fuels production is poised at the intersection of innovation and sustainability, presenting numerous challenges and opportunities. The adoption of process intensification (PI) techniques can significantly enhance efficiency, reduce environmental impact, and promote economic viability [61]. Through advanced technologies and integrated approaches.

The following section is based on the framework established by Demirel and Rosen [22]. Their work highlights how Process Intensification (PI) addresses critical challenges in e-fuel production while supporting the objectives of the 2030 Agenda and advancing the principles of the circular economy, Industry 4.0, and artificial intelligence. a) Advances in Catalysis and Reaction Engineering

PI Strategy: Utilization of advanced catalysts and innovative reactor designs.

High-Performance Catalysts: The development of high-performance catalysts is crucial for enhancing reaction rates and selectivity in e-fuels production. Leading companies like BASF and Clariant are at the forefront of developing nanostructured catalysts that offer a high surface area-to-volume ratio, leading to improved catalytic activity and reduced energy consumption. For example, the integration of metal-organic frameworks (MOFs) and zeolites can provide superior catalytic properties, enabling more efficient synthesis of e-fuels from CO_2 and renewable hydrogen. Recent studies show that employing these catalysts can increase reaction efficiency by 40 %, thereby significantly lowering operational costs [109].

Impact on the 2030 Agenda: The advancement of catalysts aligns with Goal 9 (Industry, Innovation, and Infrastructure), promoting sustainable industrialization through innovative technologies that enhance productivity and reduce environmental impact. By improving catalytic processes, we can foster cleaner and more efficient energy solutions, thereby addressing Goal 13 (Climate Action).

Impact on Industry 4.0: The implementation of advanced catalysts often involves data-driven insights, such as machine learning algorithms to optimize catalyst design and performance. This integration reflects Industry 4.0 principles by enabling smarter manufacturing processes and real-time adjustments based on data analytics.

Impact on Circular Economy: High-performance catalysts contribute to resource efficiency by enabling the use of renewable feedstocks and reducing raw material consumption. Enhanced catalyst designs also lead to lower emissions, aligning with circular economy goals by promoting sustainable resource management.

Reactor Design and Optimization: Innovative reactor designs, such as microreactors and structured catalysts, can significantly improve process efficiency. Companies like MicroFuels and Chemtrix have implemented microchannel reactors, which allow for precise control of reaction conditions, leading to higher yields and reduced by-product formation. Numerical analyses demonstrate that these advanced reactor technologies can improve energy efficiency by up to 30 % compared to conventional reactors [70]. Additionally, the integration of continuous flow reactors facilitates better heat and mass transfer, which can be crucial for exothermic reactions involved in e-fuels synthesis [119].

Impact on the 2030 Agenda: Improved reactor designs contribute to Goal 7 (Affordable and Clean Energy) by enhancing energy efficiency and supporting the transition to sustainable energy systems. Moreover, they help in meeting Goal 12 (Responsible Consumption and Production) through reduced waste generation.

Impact on Industry 4.0: Advanced reactor systems often incorporate smart sensors and control technologies, aligning with Industry 4.0 principles by enabling real-time data collection and process optimization. This technology allows for adaptive control strategies that enhance production consistency and reliability.

Impact on Circular Economy: Enhanced reactor efficiency reduces waste and energy consumption, promoting more sustainable production practices. By minimizing energy and resource use, these innovations support circular economy principles through efficient material utilization and waste reduction. b) Integration of Renewable Energy and Energy Management

PI Strategy: Advanced energy management systems and renewable energy integration.

Renewable Energy Integration: The incorporation of intermittent renewable energy sources, such as solar and wind, into e-fuels production requires advanced energy management strategies. Companies like Siemens and Tesla are developing robust systems for energy storage and grid management, facilitating the smooth integration of renewable energy into production processes. For instance, large-scale battery storage and hydrogen storage systems help balance supply and demand, ensuring a continuous and stable energy supply for electrolysis and synthesis processes. A numerical analysis indicates that utilizing advanced energy management systems can enhance overall efficiency by 20 % [75].

Impact on the 2030 Agenda: This integration supports Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action), ensuring a reliable and sustainable energy supply while reducing greenhouse gas emissions. By optimizing the use of renewable energy, we can significantly lower the carbon footprint of e-fuels production.

Impact on Industry 4.0: Advanced energy management systems facilitate the integration of smart grid technologies, improving operational efficiency and data analytics capabilities. These systems enable real-time monitoring and adjustment of energy consumption patterns, aligning with Industry 4.0 innovations.

Impact on Circular Economy: By integrating renewable energy sources, e-fuels production can reduce reliance on fossil fuels, thus promoting a more circular energy economy. Utilizing renewable resources effectively supports the transition to sustainable energy practices.

Energy Efficiency Improvements: Enhancing energy efficiency in production processes is essential for reducing costs and environmental impact. Innovations in energy recovery, such as capturing waste heat from reaction processes for preheating or power generation, can significantly improve overall energy efficiency. Companies like Schneider Electric are at the forefront of optimizing energy usage through advanced process control systems and real-time monitoring technologies [40].

Impact on the 2030 Agenda: Energy efficiency improvements promote Goal 12 (Responsible Consumption and Production) by minimizing waste and resource use, leading to a more sustainable production process. Improved energy management can also contribute to Goal 11 (Sustainable Cities and Communities) by enhancing urban energy systems.

Impact on Industry 4.0: The use of smart grid technologies and IoT-enabled devices enhances energy management, aligning with Industry 4.0 by optimizing energy consumption and operational efficiencies. This alignment supports the development of intelligent manufacturing systems that utilize data for continuous improvement.

Impact on Circular Economy: Improved energy efficiency supports the circular economy by minimizing waste and optimizing resource utilization, ensuring that materials are used effectively and sustainably.

PI Strategy: Implementation of modular systems for flexibility, scalability, and operational adaptability to renewable energy fluctuations.

1. Modular Systems: Modular systems provide flexibility not only for scaling production based on market demand and feedstock availability but also for adapting operations to the variability of renewable energy sources, such as solar and wind. Haldor Topsoe and MOL Group have been pioneers in implementing modular reactors, which are designed to handle various feedstocks (e.g., biomass, biogas) and production scales. These systems offer the ability to rapidly adjust production rates depending on the availability of renewable energy, making them well-suited for energy-intensive processes like hydrogen production and carbon capture. By responding to real-time energy fluctuations, these systems enhance the integration of renewable energy, reduce reliance on energy storage, and contribute to lowering operational costs [83].

For example, electrolyzers used in hydrogen production can increase output during periods of high wind or solar energy availability and decrease production during low-energy periods. This ramp-up/ramp-down capability allows producers to optimize the use of renewable energy, avoiding the need for costly grid energy. Modular Fischer-Tropsch reactors also enable flexibility by adjusting conversion rates of hydrogen and captured CO_2 based on energy supply [95]. This adaptability reduces energy waste and operational inefficiencies, ultimately enhancing the economic feasibility of e-fuels.

2. Flexibility Under Renewable Energy Fluctuations: The intermittent nature of renewable energy is a significant challenge for e-fuels production, as it directly impacts the availability of energy for processes like water electrolysis and CO_2 conversion. To address this, advanced process intensification (PI) strategies have been developed to enable real-time operational flexibility. For instance, hydrogen production systems can be designed to take advantage of energy surpluses (e.g., excess wind generation at night) by operating at full capacity, while during periods of low renewable output, production can be scaled down or switched to alternative energy sources, such as methane or biogas reforming [84]. This ensures continuous production while maximizing renewable energy usage.

Concrete examples of these strategies include using hybrid energy storage systems, which store excess renewable energy as chemical energy in the form of hydrogen, allowing the plant to maintain operations during periods of low energy availability. Additionally, the integration of advanced control systems enables continuous monitoring and dynamic adjustments of process parameters to align with fluctuating energy inputs [29]. Numerical simulations indicate that such flexible systems can reduce operational costs by up to 20–30 %, as they minimize energy waste, stabilize operations, and reduce reliance on external energy supplies.

Impact on the 2030 Agenda: The integration of modular, scalable, and flexible systems not only addresses technical challenges but also contributes to the sustainability goals outlined in the 2030 Agenda. The ability to adjust operations to renewable energy fluctuations supports Goal 7 (Affordable and Clean Energy) by promoting the efficient use of renewable energy sources. In addition, the scalability and adaptability of these systems align with Goal 9 (Industry, Innovation, and Infrastructure), fostering innovation in sustainable industrial practices and enhancing the resilience of energy systems. Furthermore, by reducing transportation emissions and enhancing energy efficiency, these systems contribute to Goal 13 (Climate Action), supporting efforts to mitigate climate change and reduce greenhouse gas emissions.

Impact on Industry 4.0: Modular systems facilitate agile manufacturing practices, allowing for quick adjustments to production based on real-time market demands and technology advancements, thereby enhancing overall responsiveness and efficiency.

Impact on Circular Economy: Modular systems promote localized production, reducing transportation needs and waste, thus enhancing resource efficiency and supporting circular economic models.

Scalability and Adaptability: Scalable PI technologies can adapt to advancements in renewable energy and CO_2 capture methods. For example, scalable electrolysis systems from Nel Hydrogen can be expanded as renewable energy capacity increases, ensuring continuous improvement and alignment with technological advancements [5].

Impact on the 2030 Agenda: This adaptability supports Goal 9 and Goal 13 (Climate Action) by enabling the rapid transition to sustainable energy solutions and contributing to global efforts in reducing carbon emissions.

Impact on Industry 4.0: The flexibility of modular systems aligns with Industry 4.0 by enabling rapid responses to market changes and consumer demands through agile manufacturing practices, allowing industries to adapt quickly to evolving technologies.

Impact on Circular Economy: Scalable systems contribute to circular economy initiatives by allowing for more efficient use of resources, minimizing waste, and promoting sustainable production practices.

3.1. Enhanced process control and automation

PI Strategy: Advanced process control systems for optimization.

Process Control Systems: Sophisticated process control systems enable precise management of reaction conditions, ensuring optimal performance and product quality. Companies such as Honeywell and ABB are employing real-time monitoring and control technologies, providing valuable insights into process dynamics. This capability allows for adjustments to maintain optimal operating conditions and mitigates potential issues before they impact production, potentially improving overall efficiency by 15 % [14,72].

Impact on the 2030 Agenda: Effective process control contributes to Goal 9 (Industry, Innovation, and Infrastructure) by enhancing the reliability and sustainability of production processes. Additionally, optimized control systems can improve product quality, which supports Goal 12 in promoting responsible production practices.

Impact on Industry 4.0: Real-time data analytics and AI-driven control systems embody Industry 4.0 principles, enhancing predictive maintenance and process optimization. Implementing smart technologies facilitates continuous improvement and efficiency in production.

Impact on Circular Economy: Enhanced process control can minimize waste generation and resource consumption, aligning with circular economy principles by promoting efficiency and sustainability in production processes.

Automation and Smart Technologies: Automation enhances efficiency and reliability in e-fuels production. Automated systems for feedstock handling and reaction control reduce manual intervention and minimize errors [85]. Siemens is leveraging AI and machine learning to optimize process parameters, predicting maintenance needs and enhancing operational efficiency.

Impact on the 2030 Agenda: Automation supports Goal 8 (Decent Work and Economic Growth) by enhancing productivity while maintaining safe working conditions, thus promoting sustainable industrial practices.

Impact on Industry 4.0: Automation is a cornerstone of Industry 4.0, facilitating the integration of IoT technologies, smart devices, and data analytics into manufacturing processes, leading to improved decision-making and process optimization.

Impact on Circular Economy: By reducing resource waste and improving efficiency through automation, the production process becomes more sustainable and contributes to a circular economy by promoting efficient use of materials and energy.

3.2. Collaborative research and development

PI Strategy: Formation of consortia for research and technology development.

Research Consortia: Collaborative research initiatives, such as those led by the European Institute of Innovation and Technology (EIT), focus on accelerating innovation in e-fuels production. These consortia facilitate knowledge sharing and the development of new technologies that can significantly improve production efficiency and sustainability. Collaborative projects often bring together universities, research institutions, and industry players to explore novel approaches to e-fuels production, such as integrating biogenic CO_2 sources for carbon-neutral fuel production [113].

Impact on the 2030 Agenda: Research consortia align with Goal 9 (Industry, Innovation, and Infrastructure) by promoting sustainable industrialization and fostering innovation in energy systems. By encouraging collaboration and knowledge transfer, these initiatives contribute to achieving Goal 17 (Partnerships for the Goals).

Impact on Industry 4.0: Innovation hubs leverage digital technologies to enhance collaboration and streamline R&D processes, exemplifying Industry 4.0 principles. This collaborative approach encourages interdisciplinary research and the application of advanced data analytics and AI in technology development [103].

Impact on Circular Economy: Collaborative research efforts emphasize sustainability and resource optimization, reinforcing circular economy strategies by exploring ways to close material loops and reduce waste throughout the production lifecycle.

The pursuit of process intensification in e-fuels production represents a multifaceted opportunity to enhance efficiency, sustainability, and economic viability. By integrating innovative technologies, optimizing resource utilization, and fostering collaborative efforts, the industry can address existing challenges and position itself for a sustainable future aligned with the 2030 Agenda, Industry 4.0, and the principles of the circular economy. Embracing these opportunities is essential for developing resilient energy systems capable of supporting global energy demands while minimizing environmental impacts [10].

4. Overview of cost distribution of an e-fuel production plant and the impact of PI on cost reduction

The cost distribution of an e-fuel production plant presents significant challenges in achieving economic viability, especially given the high capital and operational expenditures associated with electrolyzers, CO_2 capture systems, and energy consumption [89]. However, process intensification (PI) plays a critical role in optimizing these processes, leading to substantial cost savings, efficiency improvements, and enhanced sustainability [11].

1. Capital Costs (40 %–50 %) [97,98]

Capital expenditures (CAPEX) include investments in critical technologies such as electrolyzers, CO_2 capture systems, synthesis reactors, and supporting infrastructure. PI strategies significantly impact the reduction of CAPEX through:

Electrolyzer Efficiency and Design: By employing advanced materials and modular designs in electrolyzers, PI enhances efficiency, reducing the required size and cost of the equipment. Innovations in high-temperature electrolysis (solid oxide electrolyzers) can improve hydrogen production efficiency, reducing the need for larger, more expensive systems. These advancements can lower the capital costs of electrolyzers by up to 20 %–30 % [8].

Modular CO_2 Capture Systems: PI enables modular and scalable CO_2 capture technologies, reducing upfront investment by adapting system sizes to the specific CO_2 source. Direct air capture (DAC) systems with enhanced adsorption materials and intensified gas-liquid contactors reduce capital investments by improving the capture efficiency. PI's integration of intensified contactor designs can reduce CO_2 capture system costs by 10 %–15 % [110].

Compact Reactor Design: PI promotes compact reactor designs that increase the throughput per unit volume, reducing the required reactor size. Intensified catalytic processes, such as microchannel reactors, improve mass and heat transfer rates, leading to better reaction efficiencies. By reducing the footprint and capital requirements, reactor costs can be minimized by 15 %–20 % [28].

2. Operational Costs (40 %–50 %) [97,98]

Operational expenditures (OPEX) are a major concern due to the high energy requirements for e-fuel production. PI provides several strategies to decrease these costs:

Electricity Efficiency Through PI: The energy demand for water electrolysis and CO_2 capture remains the largest contributor to OPEX. PI addresses this by improving energy efficiency through advanced reactor designs, enhanced catalytic processes, and waste heat recovery. For instance, waste heat from exothermic synthesis reactions can be recycled to preheat water for electrolysis, reducing energy consumption by 10 %–20 %. Moreover, the use of energy-efficient catalysts in the electrolysis process can further lower electricity requirements, resulting in 5 %–10 % cost reductions [110].

Enhanced Catalytic Systems: PI-driven advancements in catalyst development, such as the use of higher-activity and longer-lasting catalysts, lead to reduced catalyst deactivation and lower replacement costs. PI can reduce the cost of catalysts by 10 %–15 %, resulting in lower operational costs over the plant's lifetime [18].

Reduced Maintenance and Labor: By integrating smart, modular systems and employing AI-driven predictive maintenance strategies, PI can reduce the need for manual labor and maintenance downtime. This can lead to a 5 %–10 % reduction in labor and maintenance costs, which are critical components of operational expenses [21].

3. Energy Integration and Process Efficiency (5 %–10 %) [97,98]

Process intensification has a direct impact on overall plant energy integration, enabling higher efficiencies and lower costs through waste heat recovery and optimized energy usage:

Heat Integration: PI encourages the integration of waste heat recovery systems to utilize heat from exothermic reactions for pre-heating feedstock or generating electricity through combined heat and power (CHP) systems. This can lead to a reduction in external energy requirements by 10 %–20 %, significantly lowering energy costs (d' [19]).

Modular Process Intensification: The integration of modular PI systems allows for increased flexibility and adaptability, enhancing the overall process efficiency and scalability. This flexibility enables better resource utilization, driving further cost reductions, particularly in balancing energy supply from renewable sources with process demand.

4. CO_2 Capture and Storage Costs (5 %–15 %) [97,98]

Process intensification offers advanced methods for improving CO_2 capture efficiency and reducing associated costs:

Improved CO_2 Capture Technology: PI enables the development of more efficient absorbents and intensified CO_2 contactor designs, reducing the energy intensity and cost of CO_2 capture by up to 15 %–20 %. This includes using higher-performance materials for DAC systems and optimizing the flow dynamics in absorption and stripping columns [71].

Through the implementation of process intensification strategies, significant cost reductions can be achieved across both capital and operational expenditures. PI contributes to a 15 %–20 % overall cost savings in e-fuel production, enhancing the economic viability of this key technology in achieving sustainable, low-carbon energy goals [45]. These savings are critical for making e-fuels competitive with traditional fossil fuels and supporting the transition to a circular, sustainable energy future.

5. Overcoming the barriers to e-Fuel adoption

To accelerate the widespread adoption of hydrogen and e-fuels, innovation and implementation efforts in e-fuel production, vehicle technologies, and associated infrastructure must be intensified [89]. Achieving this requires overcoming several significant barriers, as identified during the market consultation for this study. Below is a summary of these barriers, along with suggested strategies to mitigate them 2,38,86]: a) Economic Barriers

• High cost of e-fuels

• Uncertainty regarding future renewable electricity and CO_2 feedstock costs

• Depreciation of existing assets; need for new infrastructure b) Strategies to Overcome Economic Barriers

• Invest in R&D to develop more efficient production routes and reduce capital expenditures (CAPEX) for electrolysers.

• Acknowledge that sustainable fuels are likely to remain more expensive than current fossil fuel prices.

• Develop financial mechanisms and long-term contracts to reduce the uncertainty surrounding future energy and feedstock costs.

• Leverage volatile electricity prices by implementing flexible hydrogen production processes.

• Where feasible, share infrastructure with other sectors, such as hydrogen and methanol production, and repurpose fossil infrastructure for storage needs.

These barriers cannot be addressed by individual stakeholders alone. Stakeholders must collaborate across sectors, as cooperation is critical to overcoming these challenges. In areas such as regulatory frameworks and emission targets, collaboration may extend beyond national borders, requiring cooperation at the EU or global level.

Effective stakeholder collaboration and the formation of strategic alliances are essential for the successful transition to e-fuels. The development and application of e-fuels in transportation necessitate advancements across multiple areas: research and development (R&D), production technologies, regulatory frameworks, distribution infrastructure, and vehicle adaptation. While biofuels and hydrogen are currently being piloted and applied on a limited scale, e-fuels remain in the early stages of development. The production of e-fuels will require substantial amounts of electricity from renewable sources, and hydrogen production must be scaled up significantly, as it serves as the feedstock for all e-fuels. Further R&D is essential to identify efficient production pathways and reduce associated costs. Additionally, synergy with the chemical industry could be leveraged through the joint development of production processes and Direct Air Capture (DAC) technologies. E-methanol is a particularly promising option for early deployment, not only due to its mature production technology but also because it can serve as a versatile feedstock for producing e-diesel and e-kerosene [45]. Its applications extend beyond transportation, offering a valuable platform for various chemical sector applications. Similarly, e-diesel presents a relatively secure option as it requires minimal infrastructure modification and aligns with existing standards, thus allowing seamless integration without necessitating vehicle modifications. These benefits underscore e-methanol and e-diesel as viable initial choices for scaling up sustainable fuel production.

6. Conclusion

To conclude the discussion on the viability of e-fuels, it is essential to analyze the specific e-fuel types and the associated production technologies in terms of their scalability, cost-effectiveness, and application within various sectors. E-methanol and e-kerosene (SAF) stand out as leading candidates due to their widespread applicability and alignment with current technological trends. E-methanol, for instance, demonstrates strong potential in the maritime and chemical sectors, with lower production costs and relatively straightforward scalability when compared to other e-fuels. Studies show that producing one kilogram of e-methanol requires approximately 0.189 kg of hydrogen and 1.373 kg of CO_2, while the process benefits from reactor designs that enhance heat management and water content mitigation. This cost-effective synthesis, particularly at larger production scales, positions e-methanol as a highly viable option for decarbonizing industries dependent on liquid fuels.

On the other hand, e-kerosene and SAF are particularly relevant in the aviation sector, where they offer a sustainable alternative to conventional fossil-based jet fuels. The Fischer-Tropsch (FT) process, used to produce e-kerosene, efficiently converts syngas (CO/H_2) into liquid hydrocarbons, with studies indicating that approximately 1.36 kg of hydrogen and 14.55 kg of CO_2 are needed to produce one kilogram of SAF. Furthermore, SAF's compatibility with existing aviation infrastructure, alongside its growing adoption by airlines, makes it a key fuel for decarbonizing air travel [78]. Although SAF production is more capital-intensive, recent advancements in FT reactor design and catalyst development are expected to drive down production costs, making it increasingly competitive.

In terms of production technologies, the efficiency of the electrolyzers used in hydrogen generation plays a pivotal role in determining the overall viability of e-fuels. PEM (Proton Exchange Membrane) electrolysis, with its high efficiency and compatibility with intermittent renewable energy sources, currently stands as the most promising technology for large-scale hydrogen production. It offers significant advantages over alkaline electrolysis, which, although cost-effective, is less adaptable to fluctuations in renewable energy supply. SOEC (Solid Oxide Electrolysis Cells), while demonstrating higher electrical efficiency, is still in the developmental stage and presents challenges in terms of high operating temperatures and material costs [68].

When comparing the different electrolyzer technologies, PEM electrolysis provides a balanced combination of efficiency, flexibility, and scalability. For instance, PEM systems can achieve efficiencies of around 60–70 %, while maintaining operational flexibility with variable renewable energy sources such as wind and solar [35]. This adaptability is crucial for the cost-effective integration of renewable energy into the e-fuel production chain, making PEM-based systems highly suitable for both e-methanol and SAF production.

In conclusion, e-methanol emerges as the most viable e-fuel for industrial applications, particularly in the maritime and chemical sectors, due to its lower production costs and scalable synthesis methods. Meanwhile, e-kerosene (SAF) is the optimal choice for the aviation sector, offering a direct path to reducing carbon emissions without requiring modifications to existing infrastructure. From a technological perspective, PEM electrolysis stands out as the most efficient and flexible method for hydrogen production, providing the necessary scalability and integration with renewable energy sources, crucial for the widespread adoption of e-fuels. As research and innovation continue to improve catalyst performance and reactor designs, the overall economic and environmental feasibility of e-fuels will strengthen, positioning them as a critical component in achieving carbon-neutral energy solutions across multiple sectors.

The intensification of chemical processes in e-fuels production presents both significant challenges and promising opportunities, essential for advancing toward a sustainable energy future. As the global community accelerates efforts to meet ambitious climate targets, e-fuels are emerging as a viable, sustainable energy carrier, particularly in sectors that are difficult to decarbonize. Process intensification (PI) stands out as a key strategy to address the multifaceted challenges associated with e-fuels, offering substantial potential to improve efficiency, reduce costs, and enhance environmental sustainability [88].

6.1. Addressing challenges through process intensification

E-fuels production is confronted with several challenges, including high energy consumption, elevated production costs, and technological constraints in catalysis and CO_2 capture. PI offers promising solutions through the optimization and modernization of these processes.

Efficiency Improvements: Studies reveal that by incorporating advanced materials and innovative reactor designs, the operational efficiency of electrolyzers and synthesis reactors can be significantly improved. For instance, the use of high-performance catalysts has been shown to increase reaction rates by up to 30 %, while optimized reactor configurations can reduce energy consumption by approximately 15 % compared to traditional systems. Such gains in efficiency are pivotal in achieving economic viability, as they directly contribute to reducing the overall energy intensity of e-fuels production [108].

Cost Reduction: Reducing production costs is essential for the widespread adoption of e-fuels. PI facilitates this by leveraging cost-effective materials, enhancing reactor engineering, and streamlining process integration. Research indicates that optimized reactor designs can lower energy costs by around 20 % and capital costs by up to 10 %. Additionally, the implementation of efficient catalysts further drives down operational expenses, improving the competitiveness of e-fuels relative to conventional fossil fuels. Overall, PI-driven improvements could result in a 15–20 % reduction in production costs [76].

Environmental Impact: PI also plays a critical role in minimizing the environmental impact of e-fuels production. Advanced waste heat recovery systems can reclaim up to 50 % of the energy that would otherwise be lost, while state-of-the-art CO_2 capture technologies have achieved capture efficiencies exceeding 90 % [22]. Moreover, integrating combined heat and power (CHP) systems alongside innovative CO_2 capture methodologies can lead to a significant reduction in greenhouse gas (GHG) emissions. In some configurations, these enhancements could lower the carbon intensity of e-fuels by more than 50 % compared to conventional fossil fuel production [42].

6.2. Leveraging opportunities for advancements

The production of e-fuels is rich with opportunities for innovation, primarily driven by PI advancements. Capitalizing on these opportunities is crucial for maximizing the role of e-fuels in the future energy mix.

Modularity and Scalability: PI technologies' inherent modularity and scalability offer substantial advantages. Modular systems have the potential to reduce production costs by 15 %, while also providing the necessary flexibility to adapt to various feedstocks (such as biogas or biomass) and energy sources. These systems are also well-suited for accommodating renewable energy variability, reducing transportation emissions, and improving overall energy efficiency [91]. This adaptability is crucial for managing fluctuating energy inputs, particularly from renewable sources like wind and solar.

Technological Innovation: Ongoing research into high-temperature electrolysis, novel CO_2 capture methods, and advanced catalytic materials is driving significant advancements in PI. For example, innovations in electrolysis are expected to increase efficiency by up to 25 %, leading to substantial reductions in energy consumption and higher e-fuel yields. Furthermore, advancements in catalytic materials have the potential to improve the selectivity and efficiency of CO_2 conversion processes, further enhancing the sustainability of e-fuels production [23].

Operational Flexibility: Another major opportunity lies in the ability of PI-driven systems to adjust operations dynamically in response to renewable energy fluctuations. For example, electrolysis units can ramp up hydrogen production during periods of excess renewable energy (such as high wind output) and scale down during low-energy periods, minimizing the need for energy storage and reducing operational costs by as much as 20–30 % [42]. This operational flexibility is crucial for integrating renewable energy into e-fuels production, further enhancing its economic and environmental benefits.

Collaborative Research: Collaboration between academia, industry, and government is vital for advancing PI technologies. Public-private partnerships are projected to accelerate the rate of technology transfer and commercialization, potentially doubling the speed at which new solutions reach the market. This collaboration is essential for fostering innovation, reducing the time-to-market for emerging technologies, and continuously improving the efficiency and sustainability of e-fuels production.

6.3. Future directions and implications

The future of e-fuels production depends on overcoming current challenges and leveraging the opportunities offered by PI. The viability of e-fuels as a sustainable energy solution will be determined by the successful integration of advanced technologies, process optimization, and the development of cost-effective, environmentally friendly production methods [97,98].

Strategic Focus: A focused strategy on PI is essential for scaling up e-fuels production and achieving broader market acceptance. Research in areas such as catalyst development, reactor design, and renewable energy integration must remain a top priority. By addressing these critical areas, production capacity is projected to increase by 30 % over the next decade, positioning e-fuels as a crucial component of the low-carbon energy future [65].

Policy and Support: Supportive policies and infrastructure investments are critical to the successful implementation of PI technologies. Collaborative efforts between government entities and industry stakeholders are necessary to create an environment conducive to innovation, reduce barriers to adoption, and support the large-scale deployment of e-fuels production.

In conclusion, process intensification provides a transformative path for advancing e-fuels production. By addressing challenges related to efficiency, cost, and environmental sustainability, while capitalizing on opportunities for innovation and scalability, PI has the potential to significantly advance e-fuels as a key element in the transition to a low-carbon energy future. Ongoing research, innovation, and collaboration will be key to unlocking the full potential of e-fuels and achieving a sustainable energy landscape.

CRediT authorship contribution statement

Juan Gabriel Segovia-Hernández: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

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.

Data availability

No data was used for the research described in the article.

References

[1] I. Abdulrahman, V. Máša, S.Y. Teng, Process intensification in the oil and gas industry: a technological framework, Chem. Eng. Process. Process Intensif. 159 (2021) 108208.
[2] Adomaitis, N., Harvey, J., (2020). Global climate goals 'virtually impossible' without carbon capture – IEA, Reuters.
[3] N. Akhlaghi, G. Najafpour-Darzi, A comprehensive review on biological hydrogen production, Int. J. Hydrogen. Energy 45 (43) (2020) 22492–22512.
[4] A. Akhtar, V. Krepl, T. Ivanova, A combined overview of combustion, pyrolysis, and gasification of biomass, Energy & Fuels 32 (7) (2018) 7294–7318.
[5] E.S. Akyüz, E. Telli, M. Farsak, Hydrogen generation electrolyzers: paving the way for sustainable energy, Int. J. Hydrogen. Energy 81 (2024) 1338–1362.
[6] K. Atsonios, J. Li, V.J. Inglezakis, Process analysis and comparative assessment of advanced thermochemical pathways for e-kerosene production, Energy 278 (2023) 127868.
[7] F. Ausfelder, K. Wagemann, Power-to-fuels: e-fuels as an important option for a climate-friendly mobility of the future, Chemie ingenieur technik 92 (1–2) (2020) 21–30.
[8] J. Baier, G. Schneider, A. Heel, A cost estimation for CO_2 reduction and reuse by methanation from cement industry sources in Switzerland, Front. Energy Res. 6 (2018) 5.
[9] A. Boretti, Advancements in E-Fuel combustion systems for a sustainable energy future, Int. J. Hydrogen. Energy 79 (2024) 258–266.
[10] P.F. Borowski, Digitization, digital twins, blockchain, and industry 4.0 as elements of management process in enterprises in the energy sector, Energies. (Basel) 14 (7) (2021) 1885.
[11] S. Brynolf, M. Taljegard, M. Grahn, J. Hansson, Electrofuels for the transport sector: a review of production costs, Renewable and Sustainable Energy Reviews 81 (2018) 1887–1905.
[12] M. Bui, C.S. Adjiman, A. Bardow, E.J. Anthony, A. Boston, S. Brown, N. Mac Dowell, Carbon capture and storage (CCS): the way forward, Energy & Environmental Science, 11 (5) (2018) 1062–1176.
[13] Carbon Capture Market Overview (2024). https://www.reportlinker.com/market-report/Environmental-Services/7665/Carbon-Capture?, term=carbon%20capture%20market&matchtype=b&loc_interest=&loc_physical=1010057&utm_group=standard&utm_term=carbon%20capture%20market&utm_campaign=ppc&utm_source=google_ads&utm_medium=paid_ads&utm_content=transactionnel-4&hsa_acc=7082072004&hsa_cam=15072279998&hsa_grp=126667665021&hsa_ad=561824791810&hsa_src=g&hsa_tgt=kwd-565705808534&hsa_kw=carbon%20capture%20market&hsa_mt=b&hsa_net=adwords&hsa_ver=3&gad_source=1&gclid=CjwKCAjw6c63BhAiEiwAF0EH1C7UfRQUeLkFjqPkLOHz_w14r_icQi_K47EFpkyaqWUPwf9sG-IdgBoC-VsQAvD_BwE.
[14] X. Chen, W. Cao, Q. Zhang, S. Hu, J. Zhang, Artificial intelligence-aided model predictive control for a grid-tied wind-hydrogen-fuel cell system, IEEe Access. 8 (2020) 92418–92430.
[15] L. Colelli, V. Segneri, C. Bassano, G. Vilardi, E-fuels, technical and economic analysis of the production of synthetic kerosene precursor as sustainable aviation fuel, Energy Convers. Manage 288 (2023) 117165.
[16] Conrado, R.J., Haynes, C.A., Haendler, B.E., & Toone, E.J. (2012). Electrofuels: a new paradigm for renewable fuels. In Advanced biofuels and bioproducts (pp. 1037-1064). New York, NY: Springer New York.
[17] S. Consonni, L. Mastropasqua, M. Spinelli, T.A. Barckholtz, S. Campanari, Low-carbon hydrogen via integration of steam methane reforming with molten carbonate fuel cells at low fuel utilization, Adv. Appl. Energy 2 (2021) 100010.
[18] I. D'Adamo, M. Gastaldi, M. Giannini, A.S. Nizami, Environmental implications and levelized cost analysis of E-fuel production under photovoltaic energy, direct air capture, and hydrogen, Environ. Res. 246 (2024) 118163.
[19] F. d'Amore, A. Nava, P. Colbertaldo, C.G. Visconti, M.C. Romano, Turning CO2 from fuel combustion into e-Fuel? Consider alternative pathways, Energy Convers. Manage 289 (2023) 117170.
[20] D. Das, N. Khanna, C. Dasgupta, Biohydrogen Production, CRC Press, 2014.
[21] H.E. Delgado, V. Cappello, G. Zang, P. Sun, C. Ng, P. Vyawahare, J. Marcinkoski, Techno-economic analysis and life cycle analysis of e-fuel production using nuclear energy, Journal of CO2 Utilization 72 (2023) 102481.
[22] Y. Demirel, M.A. Rosen, Sustainable Engineering: Process Intensification, Energy Analysis, and Artificial Intelligence, CRC Press, 2023.
[23] S. Dell'Aversano, C. Villante, K. Gallucci, G. Vanga, A. Di Giuliano, E-Fuels: a Comprehensive Review of the Most Promising Technological Alternatives towards an Energy Transition, Energies. (Basel) 17 (16) (2024) 3995.
[24] C. Dobre, M. Costin, M. Constantin, A Review of Available Solutions for Implementation of Small–Medium Combined Heat and Power (CHP) Systems, Inventions, 9 (4) (2024) 82.
[25] F. Elmanakhly, A. DaCosta, B. Berry, R. Stasko, M. Fowler, X.Y. Wu, Hydrogen economy transition plan: a case study on Ontario, AIMS Energy 9 (4) (2021) 775–811.
[26] L.S. Fan, L. Zeng, W. Wang, S. Luo, Chemical looping processes for CO2 capture and carbonaceous fuel conversion–prospect and opportunity, Energy Environ. Sci. 5 (6) (2012) 7254–7280.
[27] S. Ferguson, A. Tarrant, Molten carbonate fuel cells for 90% post combustion CO2 capture from a new build CCGT, Front. Energy Res. 9 (2021) 668431.
[28] T. Galimova, R. Satymov, D. Keiner, C. Breyer, Sustainable energy transition of Greenland and its prospects as a potential Arctic e-fuel and e-chemical export hub for, Europe and East Asia. Energy 286 (2024) 129605.
[29] L. Göke, J. Weibezahn, M. Kendziorski, How flexible electrification can integrate fluctuating renewables, Energy 278 (2023) 127832.
[30] S.A. Grigoriev, V.N. Fateev, D.G. Bessarabov, P. Millet, Current status, research trends, and challenges in water electrolysis science and technology, Int. J. Hydrogen. Energy 45 (49) (2020) 26036–26058.
[31] T.M. Gür, Carbon dioxide emissions, capture, storage and utilization: review of materials, processes and technologies, Prog. Energy Combust. Sci. 89 (2022) 100965.
[32] P.C. Hallenbeck, M. Abo-Hashesh, D. Ghosh, Strategies for improving biological hydrogen production, Bioresour. Technol. 110 (2012) 1–9.
[33] Havukainen, J., & Sillman, J. (2024). E-fuels: pathway toward cleaner future. In Decarbonization Strategies and Drivers to Achieve Carbon Neutrality for Sustainability (pp. 283–297). Elsevier.
[34] G. Hering, B. Montgomery, First Major US Hydrogen-Burning Power Plant Nears Completion in Ohio, S&P Global Platts Media, 2021.
[35] L.E. Hombach, L. Doré, K. Heidgen, H. Maas, T.J. Wallington, G. Walther, Economic and environmental assessment of current (2015) and future (2030) use of E-fuels in light-duty vehicles in Germany, J. Clean. Prod. 207 (2019) 153–162.
[36] Hyzon Motors Reports (2023) https://investors.hyzonfuelcell.com/financials/quarterly-results/default.aspx.
[37] IEA, Energy Technology Perspectives 2020, p. 174. https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf.
[38] S. Inac, A. Midilli, The integrated hydro-solar e-fuel production for a tea factory: preliminary design and thermodynamic analysis, Int. J. Hydrogen. Energy 67 (2024) 979–990.
[39] T. Jacobs, Canadian Operator Works To Transform an Oil Field Into a Hydrogen Factory, Journal of Petroleum Technology 73 (03) (2021) 38–40.
[40] S.M. Jarvis, S. Samsatli, Technologies and infrastructures underpinning future CO2 value chains: a comprehensive review and comparative analysis, Renewable and Sustainable Energy Reviews 85 (2018) 46–68.
[41] C.M. Kalamaras, A.M. Efstathiou, Hydrogen production technologies: current state and future developments, in: Conference papers in science 2013, Hindawi Publishing Corporation, 2013 690627.
[42] F.M. Kanchiralla, S. Brynolf, A. Mjelde, Role of biofuels, electro-fuels, and blue fuels for shipping: environmental and economic life cycle considerations, Energy Environ. Sci. 17 (17) (2024) 6393–6418.
[43] P.R. Kapadia, M.S. Kallos, C. Leskiw, I.D. Gates, Potential for hydrogen generation during in situ combustion of bitumen, in: SPE Europec featured at EAGE Conference and Exhibition (pp. SPE-122028), SPE, 2009.
[44] I.K. Kapdan, F. Kargi, Bio-hydrogen production from waste materials, Enzyme Microb. Technol. 38 (5) (2006) 569–582.
[45] V. Karbassi, P.A. Trotter, G. Walther, Diversifying the African energy system: economic versus equitable allocation of renewable electricity and e-fuel production, Applied Energy, 350 (2023) 121751.
[46] Kayfeci, M., A. Keçebaş and M. Bayat, Hydrogen production, in Solar Hydrogen Production, ed. F. Calise, M. D.D'Accadia, M. Santarelli, A. Lanzini and D. Ferrero, Academic Press, 2019, ch. 3, pp. 45–83.
[47] M.-K. Kazi, F. Eljack, M.M. El-Halwagi, M. Haouari, Green hydrogen for industrial sector decarbonization: costs and impacts on hydrogen economy in Qatar, Comput. Chem. Eng. 145 (2021) 107144.
[48] B. Kazmi, T. Sadiq, S.A.A. Taqvi, S. Nasir, M.M. Khan, S.R. Naqvi, H. AlMohamadi, Towards a sustainable future: bio-hydrogen production from food waste for clean energy generation, Process Safe. Environ. Protect. 183 (2024) 555–567.
[49] Z.Y. Kong, E. Sánchez-Ramírez, J.Y. Sim, J. Sunarso, J.G. Segovia-Hernández, The importance of process intensification in undergraduate chemical engineering education, Digital Chem. Eng. 11 (2024) 100152.
[50] A. Kovač, M. Paranos, D. Marciuš, Hydrogen in energy transition: a review, Int. J. Hydrogen. Energy 46 (16) (2021) 10016–10035.
[51] T. Kume, Y. Ikeda, T. Iseki, H. Yakabe, H. Tanaka, H. Hikosaka, M. Ito, Performance evaluation of membrane on catalyst module for hydrogen production from natural gas, Int. J. Hydrogen. Energy 38 (14) (2013) 6079–6084.
[52] J. Li, H. Zhang, Z. Gao, J. Fu, W. Ao, J. Dai, CO2 capture with chemical looping combustion of gaseous fuels: an overview, Energy & Fuels 31 (4) (2017) 3475–3524.
[53] Linjala, O. (2021). Review on post-combustion carbon capture technologies and capture of biogenic CO_2 using pilot-scale equipment. Master's Thesis, LUT University.
[54] Y. Liu, Z. Dai, Z. Zhang, S. Zeng, F. Li, X. Zhang, X. Ji, Ionic liquids/deep eutectic solvents for CO2 capture: reviewing and evaluating, Green Energy & Environment 6 (3) (2021) 314–328.
[55] T. Lockwood, A compararitive review of next-generation carbon capture technologies for coal-fired power plant, Energy Procedia 114 (2017) 2658–2670.
[56] E.A. López-Guajardo, F. Delgado-Licona, A.J. Álvarez, K.D. Nigam, A. Montesinos-Castellanos, R. Morales-Menendez, Process intensification 4.0: a new approach for attaining new, sustainable and circular processes enabled by machine learning, Chemical Engineering and Processing-Process Intensification 180 (2022) 108671.
[57] U.A. Makhova, M.A. Ershov, A.V. Ilin, V.D. Savelenko, N.O. Burov, M. M. Lobashova, T.M. Abdellatief, Green Approach to Alternative Fuel for Jet Fuel

Quality Issues in the Perspective of Decarbonization, Process Safety and Environmental Protection (2024).
[58] S. Manish, R. Banerjee, Comparison of biohydrogen production processes, Int. J. Hydrogen. Energy 33 (1) (2008) 279–286.
[59] C.M. Masuku, L.T. Biegler, Recent advances in gas-to-liquids process intensification with emphasis on reactive distillation, Curr. Opin. Chem. Eng. 25 (2019) 95–100.
[60] F. Meng, Y. Meng, T. Ju, S. Han, L. Lin, J. Jiang, Research progress of aqueous amine solution for CO2 capture: a review, Renewable and Sustainable Energy Reviews 168 (2022) 112902.
[61] M.A. Murmura, A. Brasiello, Challenges and opportunities of process intensification for the conversion of waste CO_2 to liquid fuels, Chemical Engineering and Processing-Process Intensification 186 (2023) 109329.
[62] H. Nazir, C. Louis, S. Jose, J. Prakash, N. Muthuswamy, M.E. Buan, A.M. Kannan, Is the H2 economy realizable in the foreseeable future? Part I: H2 production methods, Int. J. Hydrogen. Energy 45 (27) (2020) 13777–13788.
[63] Neste Annual Report, 2023 https://www.neste.com/investors/financials/annual-report.
[64] Nyholm, F., & Saxén, H. (2024). Evaluation Method for Power-to-Liquids Concepts for e-Kerosene Production. In Computer Aided Chemical Engineering (Vol. 53, pp. 3349–3354). Elsevier.
[65] D. Oke, J.B. Dunn, T.R. Hawkins, Reducing Economy-Wide Greenhouse Gas Emissions with Electrofuels and Biofuels as the Grid Decarbonizes, Energy & Fuels 38 (7) (2024) 6048–6061.
[66] D.F. Ordóñez, T. Halfdanarson, C. Ganzer, N. Shah, N. Mac Dowell, G. Guillén-Gosálbez, Evaluation of the potential use of e-fuels in the European aviation sector: a comprehensive economic and environmental assessment including externalities, Sustain. Energy Fuels. 6 (20) (2022) 4749–4764.
[67] A.I. Osman, M. Hefny, M.I.A. Abdel Maksoud, A.M. Elgarahy, D.W. Rooney, Recent advances in carbon capture storage and utilisation technologies: a review, Environ. Chem. Lett. 19 (2) (2021) 797–849.
[68] A.S. Oyewo, G. Lopez, M. ElSayed, T. Galimova, C. Breyer, Power-to-X Economy: green e-hydrogen, e-fuels, e-chemicals, and e-materials opportunities in Africa, Energy Reports, 12 (2024) 2026–2048.
[69] N. Panichkittikul, V. Mariyappan, W. Wu, Y. Patcharavorachot, Improvement of biohydrogen production from biomass using supercritical water gasification and CaO adsorption, Fuel 361 (2024) 130724.
[70] G. Papanikolaou, G. Centi, S. Perathoner, P. Lanzafame, Transforming catalysis to produce e-fuels: prospects and gaps, Chinese Journal of Catalysis 43 (5) (2022) 1194–1203.
[71] J. Peacock, R. Cooper, N. Waller, G. Richardson, Decarbonising aviation at scale through synthesis of sustainable e-fuel: a techno-economic assessment, Int. J. Hydrogen. Energy 50 (2024) 869–890.
[72] M. Pereira, D. Limón, T. Alamo, L. Valverde, C. Bordons, Economic model predictive control of a smartgrid with hydrogen storage and PEM fuel cell, in: IECON 2013-39th Annual Conference of the IEEE Industrial Electronics Society, IEEE, 2013, pp. 7920–7925.
[73] R. Pinsky, P. Sabharwall, J. Hartvigsen, J O'Brien, Comparative review of hydrogen production technologies for nuclear hybrid energy systems, Progress in Nuclear Energy 123 (2020) 103317.
[74] M. Prussi, L. Laveneziana, L. Testa, D. Chiaramonti, Comparing e-fuels and electrification for decarbonization of heavy-duty transports, Energies. (Basel) 15 (21) (2022) 8075.
[75] A. Ramirez, S.M. Sarathy, J. Gascon, CO_2 derived E-fuels: research trends, misconceptions, and future directions, Trends. Chem. 2 (9) (2020) 785–795.
[76] S.S. Ravi, J. Mazumder, J. Sun, C. Brace, J.W. Turner, Techno-Economic assessment of synthetic E-Fuels derived from atmospheric CO2 and green hydrogen, Energy Convers. Manage 291 (2023) 117271.
[77] Richter, S., Planke, K., Österle, I., Braun-Unkhoff, M., Prause, J., & Aigner, M. (2021, November). E-fuels for the Energy Transition in the Transport Sector–Properties and Application: current State of Research. In 13th International Colloquium Fuels: Conventional and Future Energy for Automobiles (p. 177). expert verlag.
[78] P. Runge, C. Sölch, J. Albert, P. Wasserscheid, G. Zöttl, V. Grimm, Economic comparison of different electric fuels for energy scenarios in 2035, Appl. Energy 233 (2019) 1078–1093.
[79] F. Safari, I. Dincer, A review and comparative evaluation of thermochemical water splitting cycles for hydrogen production, Energy Convers. Manage 205 (2020) 112182.
[80] K. Salbrechter, T. Schubert, Combination of b-fuels and e-fuels—A technological feasibility study, Energies. (Basel) 14 (17) (2021) 5250.
[81] N. Sánchez-Bastardo, R. Schlögl, H. Ruland, Methane pyrolysis for zero-emission hydrogen production: a potential bridge technology from fossil fuels to a renewable and sustainable hydrogen economy, Ind. Eng. Chem. Res. 60 (32) (2021) 11855–11881.
[82] N. Sazali, Emerging technologies by hydrogen: a review, Int. J. Hydrogen. Energy 45 (38) (2020) 18753–18771.
[83] Y.T. Shah, Modular Systems For Energy and Fuel Recovery and Conversion, CRC Press, 2019.
[84] S. Shahzad, E. Jasińska, Renewable Revolution: a Review of Strategic Flexibility in Future Power Systems, Sustainability. 16 (13) (2024) 5454.
[85] J. Scheelhaase, S. Maertens, W. Grimme, Synthetic fuels in aviation–Current barriers and potential political measures, Transportation Research Procedia 43 (2019) 21–30.
[86] K. Shi, B. Guan, Z. Zhuang, J. Chen, Y. Chen, Z. Ma, Z. Huang, Perspectives and Outlook of E-fuels: production, Cost Effectiveness, and Applications, Energy & Fuels 38 (9) (2024) 7665–7692.
[87] P. Schmidt, W. Weindorf, A. Roth, V. Batteiger, F. Riegel, Power-to-Liquids Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel, German Environment Agency, Berlin, 2016.
[88] J.G. Segovia-Hernández, S. Hernández, E. Cossío-Vargas, E. Sánchez-Ramírez, Challenges and opportunities in process intensification to achieve the UN's 2030 agenda: goals 6, 7, 9, 12 and 13, Chem. Eng. Process. Process Intensif. (2023) 109507.
[89] J.G. Segovia - Hernández, N. Ramírez - Corona, V. Aristizábal - Marulanda, "Contributions of Chemical Engineering to Sustainability", Springer, 2024.
[90] R. Shaw, S. Mukherjee, The development of carbon capture and storage (CCS) in India: a critical review, Carbon Capture Science & Technology 2 (2022) 100036.
[91] K. Shi, B. Guan, Z. Zhuang, J. Chen, Y. Chen, Z. Ma, Z. Huang, Perspectives and Outlook of E-fuels: production, Cost Effectiveness, and Applications, Energy & Fuels 38 (9) (2024) 7665–7692.
[92] N.S. Sifat, Y. Haseli, A critical review of CO_2 capture technologies and prospects for clean power generation, Energies. (Basel) 12 (21) (2019) 4143.
[93] V. Singh, D. Das, Potential of hydrogen production from biomass, Science and engineering of hydrogen-based energy technologies (2019) 123–164.
[94] H. Singh, C. Li, P. Cheng, X. Wang, Q. Liu, A critical review of technologies, costs, and projects for production of carbon-neutral liquid e-fuels from hydrogen and captured CO_2, Energy Adv. 1 (9) (2022) 580–605.
[95] Smolinka, T., Ojong, E.T., & Garche, J. (2015). Hydrogen production from renewable energies—Electrolyzer technologies. In Electrochemical Energy Storage For Renewable Sources and Grid Balancing (pp. 103–128). Elsevier.
[96] X.Y.D. Soo, J.J.C. Lee, W.Y. Wu, L. Tao, C. Wang, Q. Zhu, J. Bu, Advancements in CO2 capture by absorption and adsorption: a comprehensive review, J. CO2 Utilization 81 (2024) 102727.
[97] A. Stankiewicz, T. Van Gerven, G. Stefanidis, The Fundamentals of Process Intensification, John wiley & sons, 2019.
[98] A. Stankiewicz, The principles and domains of process intensification, Chem. Eng. Prog. 116 (3) (2020) 23–28.
[99] E. Strantzali, G.A. Livanos, K. Aravossis, A Comprehensive Multicriteria Evaluation Approach for Alternative Marine Fuels, Energies. (Basel) 16 (22) (2023) 7498.
[100] I. Sullivan, A. Goryachev, I.A. Digdaya, X. Li, H.A. Atwater, D.A. Vermaas, C. Xiang, Coupling electrochemical CO2 conversion with CO2 capture, Nat. Catal. 4 (11) (2021) 952–958.
[101] E. Swiderski, B. Stengel, F. Pinkert, B. Buchholz, Influence of e-fuels on flame structures and combustion processes of large diesel engines, MTZ worldwide 83 (5) (2022) 54–61.
[102] H. Thomas, Options For Producing Low-Carbon Hydrogen At Scale, The Royal Society, 2018.
[103] M.N. Uddin, F. Wang, Fuelling a Clean Future: a Systematic Review of Techno-Economic and Life Cycle Assessments in E-Fuel Development, Applied Sciences 14 (16) (2024) 7321.
[104] F. Ueckerdt, C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, G. Luderer, Potential and risks of hydrogen-based e-fuels in climate change mitigation, Nat. Clim. Chang. 11 (5) (2021) 384–393.
[105] U.S. DOE, Hydrogen Program Plan, 2020.
[106] U.S. DOE, DOE Technical Targets for Hydrogen Production from Thermochemical Water Splitting, 2021a, https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-thermochemical-water-splitting.
[107] U.S. DOE, DOE Technical Targets for Hydrogen Production from Electrolysis, 2021b, https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis.
[108] F. Ueckerdt, C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, G. Luderer, Potential and risks of hydrogen-based e-fuels in climate change mitigation, Nat. Clim. Chang. 11 (5) (2021) 384–393.
[109] S. Van Paasen, M. Infantino, J. Yao, S.H. Leenders, J.M. van de Graaf, A. Klingler, H. Hofbauer, Development of the solid sorbent technology for post combustion CO2 capture towards commercial prototype, International Journal of Greenhouse Gas Control 109 (2021) 103368.
[110] R. Verbeek, M. Verbeek, R. de Kler, K. van Kranenburg, R. Smokers, Power-2-Fuel Cost Analysis, SmartPort, 2020. Technical Report.
[111] R. Viscardi, C. Bassano, G. Nigliaccio, P. Deiana, The potential of E-fuels as future fuels, ENEA Energ. Ambiente Innov 1 (2021) 112–116.
[112] S.L. Worman, L.F. Pratson, J.A. Karson, W.H. Schlesinger, Abiotic hydrogen (H_2) sources and sinks near the Mid-Ocean Ridge (MOR) with implications for the subseafloor biosphere, Proceedings of the National Academy of Sciences 117 (24) (2020) 13283–13293.
[113] H. Wu, Energy & Fuels Launches the Series of Virtual Special Issues on Recent Advances in Selected Energy Research Areas, Energy & Fuels 35 (1) (2020) 1–2.
[114] X. Xu, Q. Zhou, D. Yu, The future of hydrogen energy: bio-hydrogen production technology, Int. J. Hydrogen. Energy 47 (79) (2022) 33677–33698.
[115] Y. Yamauchi, K. Akiyama, Innovative zero-emission coal gasification power generation project, Energy Procedia 37 (2013) 6579–6586.
[116] M. Zaman, J.H. Lee, Carbon capture from stationary power generation sources: a review of the current status of the technologies, Korean Journal of Chemical Engineering 30 (2013) 1497–1526.
[117] X. Zhang, Current status of stationary fuel cells for coal power generation, Clean Energy 2 (2) (2018) 126–139.
[118] K. Zhang, R. Wang, A critical review on new and efficient adsorbents for CO2 capture, Chemical Engineering Journal (2024) 149495.

[119] J. Zhao, D. Wang, L. Zhang, M. He, W. Ma, S. Zhao, Microwave-enhanced hydrogen production: a review, RSC. Adv. 13 (22) (2023) 15261–15273.
[120] Y. Zhou, S. Searle, N. Pavlenko, Current and future cost of e-kerosene in the United States and Europe, I: International council on clean transportation Working paper (2022) 14.
[121] V. Zgonnik, V. Beaumont, E. Deville, N. Larin, D. Pillot, K.M. Farrell, Evidence for natural molecular hydrogen seepage associated with Carolina bays (surficial, ovoid depressions on the Atlantic Coastal Plain, Province of the USA), Prog. Earth. Planet. Sci. 2 (2015) 1–15.
[122] V. Zgonnik, The occurrence and geoscience of natural hydrogen: a comprehensive review, Earth. Sci. Rev. 203 (2020) 103140.
[123] U.K. Zore, S.G. Yedire, N. Pandi, S. Manickam, S.H. Sonawane, A review on recent advances in hydrogen energy, fuel cell, biofuel and fuel refining via ultrasound process intensification, Ultrason. Sonochem. 73 (2021) 105536.