

VTT Technical Research Centre of Finland

Next generation of polyolefin plastics: improving sustainability with existing and novel feedstock base

Reznichenko, Alexander; Harlin, Ali

Published in:
SN Applied Sciences

DOI:
[10.1007/s42452-022-04991-4](https://doi.org/10.1007/s42452-022-04991-4)

Published: 01/04/2022

Document Version
Publisher's final version

License
CC BY

[Link to publication](#)

Please cite the original version:

Reznichenko, A., & Harlin, A. (2022). Next generation of polyolefin plastics: improving sustainability with existing and novel feedstock base. *SN Applied Sciences*, 4(4), [108]. <https://doi.org/10.1007/s42452-022-04991-4>



VTT
<http://www.vtt.fi>
P.O. box 1000FI-02044 VTT
Finland

By using VTT's Research Information Portal you are bound by the following Terms & Conditions.

I have read and I understand the following statement:

This document is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of this document is not permitted, except duplication for research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered for sale.



Research Article

Next generation of polyolefin plastics: improving sustainability with existing and novel feedstock base

Alexander Reznichenko¹ · Ali Harlin¹ 

Received: 21 June 2021 / Accepted: 8 February 2022

Published online: 17 March 2022

© The Author(s) 2022 [OPEN](#)

Abstract

In this account, we present an overview of existing and emerging olefin production technologies, comparing them from the standpoint of carbon intensity, efficiency, feedstock type and availability. Olefins are indispensable feedstock for manufacture of polyolefin plastics and other base chemicals. Current methods of olefin production are associated with significant CO₂ emissions and almost entirely rely of fossil feedstock. In order to assess potential alternatives, technical and economic maturity of six principal olefin production routes are compared in this paper. Coal (brown), oil and gas (grey), biomass (green), recycled plastic (pink) as well as carbon capture and storage (purple) and carbon capture and utilization (blue) technologies are considered. We conclude that broader adoption of biomass based “green” feedstock and introduction of recycled plastic based olefins may lead to reduced carbon footprint, however adoption of best available technologies and introduction of electrocracking to existing fossil-based “grey” olefin manufacture process can be the way to achieve highest impact most rapidly. Adoption of Power-to-X approaches to olefins starting from biogenic or atmospheric CO₂ and renewable H₂ can lead to ultimately carbon-neutral “blue” olefins in the long term, however substantial development and additional regulatory incentives are necessary to make the solution economically viable.

Article highlights

- In this account, we introduce a color coding scheme to differentiate and compare carbon intensity and feedstock types for some of the main commercial and emerging olefin production routes.
- Most viable short term improvements in CO₂ emissions of olefin production will be achieved by discouraging “brown” coal based production and improving efficiency of “grey” oil and gas based processes.
- Gradual incorporation of green and recycled feedstock to existing olefin production assets will allow to achieve substantial improvements in carbon efficiency in longer term.

Key words Olefins · Ethylene · Propylene · Production · Alternative feedstocks · Carbon intensity

1 Introduction

Ethylene and propylene are the two largest volume petrochemicals in the world, with particular relevance to industrial manufacture of polyolefins. Conventionally, the major

fraction of ethylene and propylene is produced via the thermal cracking of petroleum and natural gas feedstock [1]. Well-known environmental considerations, new directives and tighter regulations drive the interest in development of new industrial processes with lower carbon

✉ Ali Harlin, ali.harlin@vtt.fi | ¹VTT Technical Research Centre of Finland, Espoo, Finland.



emissions and reduced fossil feeds consumption. In this context, possibility to produce ethylene and propylene from renewable feedstocks and waste including recycled plastics and further with processes applying low-carbon energy is of interest. These developments may lead to a totally new generation of sustainable polyolefin plastics. In this account, we will review and compare the impact of potential scenarios introducing alternatives to the “brown” and “grey” fossil-based ethylene and propylene.

Despite growing attention to the development of biobased polymer solutions [2] as potential replacement to at least a fraction of 70 Mt PP and 110 Mt PE produced annually [3], such replacement is unlikely occur to a significant extent within next several decades. Primary reasons are unmatched cost and performance of polyolefin based resins and slow commercialization of biobased alternatives such as polylactic acid (PLA), thermoplastic starch and polyhydroxyalkanoates (PHA) [4]. It is therefore of paramount importance to consider alternative sustainable feedstocks for the manufacture of ethylene and propylene as primary raw materials for the polyolefin production. We are convinced that the near-to-mid-term “replacements” for the existing polyolefins shall still be polyolefins prepared from non-fossil feedstocks or recycled monomers.

In order to distinguish between different types of industrial hydrogen, a use of different colors to describe the production method and carbon footprint have been introduced in the literature. The most common terms are green, blue and grey hydrogen [5]. Similar nomenclature has been used to differentiate different types of ammonia [6]. To our knowledge, no such systematic “color coding” scheme has been adopted e.g. for ethylene and propylene, with an exception of the term “green ethylene” which has been in use for over 10 years primarily referring to ethylene produced via catalytic dehydration of bioethanol [7]. Herein, we would like to propose the following system to distinguish different types of olefin feedstock, namely

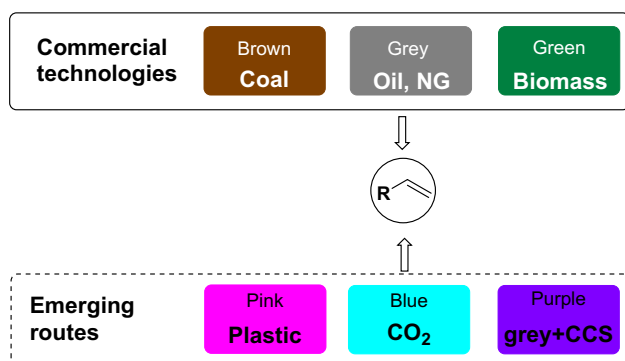


Fig. 1 Six feedstock types for olefin manufacture considered in this review. NG stands for natural gas, CCS for carbon capture and storage

brown, grey, green, pink, blue and purple olefins (Fig. 1). This simple classification can contribute to streamlined product branding, increased consumer awareness and will eventually serve as a structure for future governmental and regulatory practices.

In the next section of this account, we describe basic principles and analyze the state of technical and commercial readiness of six principal olefin production routes, including both commercial and emerging technologies. Overall comparative assessment of the possible impact on carbon intensity of olefin and polyolefin production via various routes and feedstock combinations is provided in concluding section.

2 Commercial technologies

2.1 Grey olefins

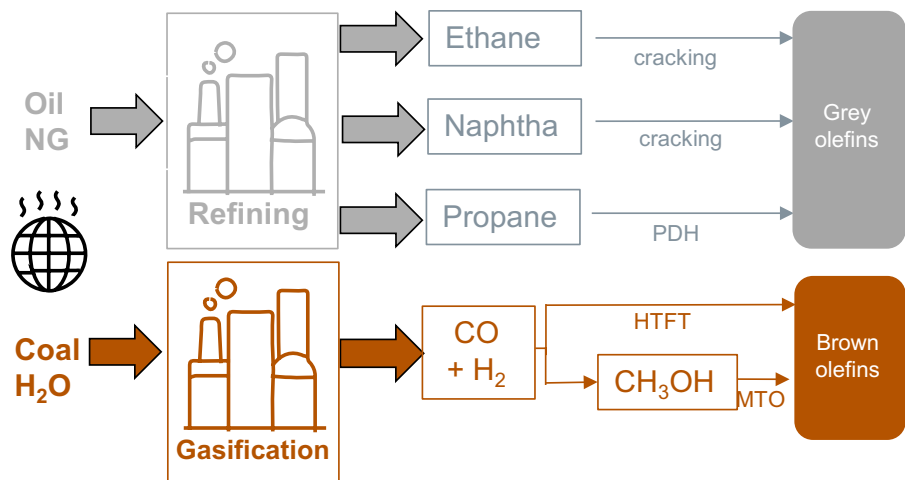
Most common, oil or natural gas (NG) based “grey” ethylene is produced mainly by thermal cracking of hydrocarbons in the presence of steam [8]. Ethylene production by the thermal cracking of naphtha is an energy-intensive process (up to 40 GJ heat per ton ethylene), leading to significant formation of coke and nitrogen oxide (NO_x), along with 1.6–2 kg of carbon dioxide (CO₂) process emissions per kilogram of ethylene produced [9].

The olefin industry is one of the largest consumers of primary energy, resulting in a total of 30% of direct CO₂ emitted from chemical plants [10]. The indirect CO₂ emissions attributed to electricity consumption by olefin production processes is roughly 12% of the total CO₂ emissions of chemical and petrochemical plants [11].

Ethylene is the main product of steam cracking, and the process also yields significant amounts of propylene and butylenes, depending on the feedstock [12]. Propylene is primarily produced as a co-product of naphtha cracking. In addition, on-purpose propylene production technologies such as propane dehydrogenation (PDH) and metathesis are used industrially. As cracking plants worldwide are being increasingly converted to ethane as a main feedstock, a demand for on-purpose propylene production is growing since ethane cracking is highly selective towards ethylene [13]. Figure 2 depicts major relevant routes to both grey and brown fossil based olefins.

Energy intensive steps of olefin production via steam cracking are pyrolysis, quenching, compression and separation [9]. Over several decades, olefin production industry has been gradually adopting incremental improvements in overall process efficiency by optimizing feedstock, improving heat recovery and separation efficiency, reducing coke formation, etc. It is estimated that adoption of best available technologies (BAT) may lower energy costs to 12 GJ/t

Fig. 2 Principal scheme for fossil-based grey and brown olefin routes



ethylene [14]. Current European average energy consumption level is 12.2 GJ/t, whereas the world average is at 13.8 GJ/t, hence it can be estimated that global adoption of BAT across the industry may lead to 585 kt/a CO₂ emission savings [15].

While adoption of BAT can bring a significant short-term sustainability improvement to the production of grey olefins, introduction of disruptive technologies such as replacing gas fired furnaces with inductive or resistive electric heating can, depending on electricity applied, offer CO₂ emission reduction of up to 90% as reported by BASF corporation [16]. In addition to electrocracking which is currently explored by several industrial players [17], an innovative path to electrifying the cracking process via Rotor Dynamic Reactor as a turbomechanical approach has been recently proposed [18].

Although using electricity produced from renewable sources reduces cracker emissions, a major challenge in developing electrical cracker technology is to ensure that the solution is technologically and economically viable against the existing process. As pointed out in an excellent recent review by Van Geem and co-authors, introduction of advanced manufacturing techniques such as high emissivity coatings, 3D coil set ups and novel furnace designs can bring substantial fuel savings (up to 30%) to the conventional cracker operations without relying on technologies still under basic development (electrocracking) [19].

Growing availability of shale gas has revolutionized the petrochemical production industry in the 2010s and has led to significant added capacity for the olefin crackers, especially in US [20]. It can therefore be expected that expanded cracker fleet will remain in the operation during at least several decades to come. In addition to implementation of BAT to reduce carbon footprint of “grey” olefins, gradual transition towards non-fossil or recycled feedstock such as renewable bio-naphtha, renewable propane or liquefied plastic waste as a feedstock to the crackers can all

be a practical path to reduce olefin carbon footprint while utilizing existing asset base. These alternatives will be discussed in the subsequent subchapters.

2.2 Brown olefins

Coal gasification (brown) route remains industrially significant for the production of synthesis gas and olefins. Two primary conversion technologies are most relevant and mature at present:

- “Brown” syngas conversion to methanol, followed by methanol-to-olefins (MTO) process.
- Coal gasification with High Temperature Fischer-Tropsch (HTFT) process.

Methanol-to-olefins (MTO) reaction is among most important C1 conversion routes enabling the production of basic olefins and petrochemicals from coal and natural gas [21]. Many institutions and companies have put great effort to the research and development of MTO reaction since it was pioneered by Mobil Corporation in 1977 [22]. Brown olefins via MTO route represent substantial and growing share of olefin manufacture in China, in particular in coal-rich regions of the country [23, 24]. It must be pointed out that coal-to-olefins (CTO) process is by far more carbon intensive compared to e.g. naphtha cracking, and should ideally be discouraged by implementation of carbon tax or mandatory carbon capture and storage (CCS) technologies [24]. Without such governmental restrictions, brown olefins remain economically feasible and represent up to 40% of olefin capacity in China.

Fischer-Tropsch (FT) process can be used to convert synthesis gas (syngas) directly into olefins, or to produce different products that can be used for the production of olefins (e.g. liquefied petroleum gas and intermediate oxygenated liquids) [25]. The product mixture of the FT

process depends on the catalyst, process conditions (pressure and temperature), type of reactor, and the synthesis gas composition [26, 27]. HTFT process using iron catalysts results in highest ($\geq 50\%$) olefin content in FT crude. MTO route holds some advantage over HTFT as the latter results in a complex product mixture containing light and heavy olefins, paraffins, oxygenates and FT-water. Sasol is currently using the HTFT process at their Secunda complex, with an iron-based catalyst, allowing for integrated production of fuels, olefins and chemicals from coal [28].

Despite high carbon intensity, “brown” olefin processes have good potential to serve as a basis for low carbon transformation of olefin value chain. Major syngas conversion technologies of the brown route such as methanol synthesis, MTO and FT process are technically mature and can readily be used for upgrading of syngas produced from non-coal (or non-fossil) feedstock, including gasified biomass (green), CO_2 (blue) and plastic waste (pink). Such possibilities will be discussed in detail in the subsequent subchapters.

2.3 Green olefins

Several routes have been proposed for the production of ethylene from renewable feedstock, but the most promising are: the dehydration of ethanol obtained by fermentation of sugar, starch or cellulose [29]; upgrading and cracking of hydrotreated bio oils and the dehydration of methanol obtained from any biomass via gasification to synthesis gas (MTO process) [30]. Principal routes are depicted in Fig. 3.

Bioethanol is mostly used as a biofuel for transport (in pure state or blended in different proportions with conventional fuel), or as an octane enhancing additive in motor vehicles to improve performance [31]. Techno-economic analysis of ethanol-to-ethylene reveals that this route cannot be presently competitive with grey ethylene produced at world scale steam crackers [32]. However, ethanol dehydration could be of interest for relatively

small-scale production in an area where public policy encouraged the development of a chemical industry based on local agricultural sources. As of 2020, 200 kt/a of green PE is produced by Braskem from sugarcane-derived ethanol and is marketed in a variety of low and high density grades [33, 34].

Renewable methanol can be produced from the gasification of biomass to synthesis gas. In theory, any feedstock containing carbon and hydrogen can be used, but because the production of methanol is a cost intensive process, different low-value waste streams are preferred, e.g. black liquor, old wood or biowaste [35]. Technical aspects of biomass gasification, syngas cleaning and integration with heat production has been researched in detail for over several decades. In particular, cleaning and conditioning of syngas to make it suitable for catalytic conversions is among most challenging and cost intensive process steps [36, 37]

Downstream technology to convert methanol to olefins is mature and available to be applied on a commercial scale, as discussed in the previous subchapter [38, 39]. Alternatively, FT route to olefins can be used in combination with biomass gasification [40]. While biomass gasification followed by MTO or FT is a scalable solution, major challenge is reaching economic profitability. Techno-economic calculations performed at VTT suggest a need for an extra “green” premium price for the bio-olefin of up to 100 €/t to make the gasification/MTO route economically viable [30]. Biomass gasification for synthesis applications is still under active development aiming to improve process economics by using small to medium scale decentralized gasification/biocrude production with improved thermal efficiency [41]. Simultaneous heat, power, and water integration is essential for the gasification plants to become more favorable economically [42].

Bio oils originating from edible and nonedible biomass can serve as sustainable non-fossil based raw material to produce fuel and chemicals utilizing existing asset base. Ideal, drop-in solution would be a direct feed of bio oils to either steam cracking [43, 44] or a catalytic cracking [45]

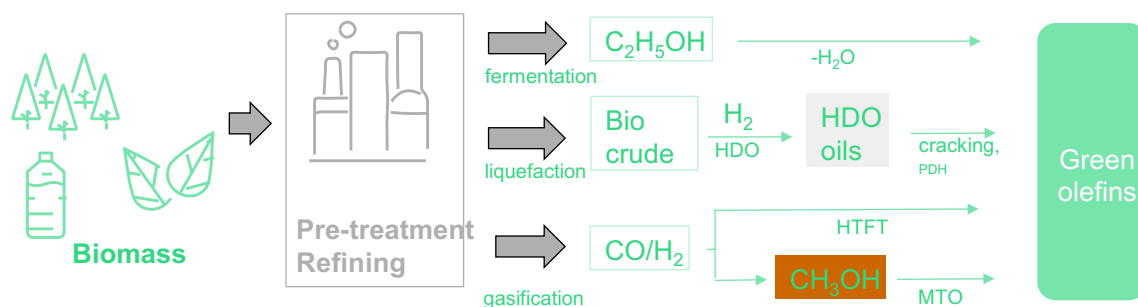


Fig. 3 Main conversion pathways in biomass-to-olefins (green) route

process to produce olefins. However, reports on direct cracking of bio oils are scarce and mostly limited to laboratory scale studies. Major challenge is vastly different composition of bio oils, in particular the presence of varied amount of oxygen. Co-feeding with a petroleum based feedstock can provide a partial solution, however only low amount of high-oxygen content bio-oil is miscible to the hydrocarbon-containing feed, and therefore feeding to fixed-bed systems such as hydrotreater in large volumes is problematic [46].

It is now universally accepted that oxygen containing bio oils need to undergo catalytic hydrodeoxygenation (HDO) in order to become processable at existing refineries and crackers [47, 48]. Liquefaction of lignocellulosic biomass via pyrolysis, catalytic pyrolysis or hydrothermal processes has become a technically mature process and respective bio oils are available at commercial scale. Unfortunately, bio-oils from liquefied lignocellulosic biomass typically feature high oxygen content (20–50 wt.%, depending on the biomass liquefaction process), thus relatively intensive HDO upgrading step is necessary to use existing refinery processes for the further processing [49]. Substantial amount of hydrogen and harsh reaction conditions are needed for the upgrading step, making overall production route more challenging [49]. To date, conversion of lignocellulosic bio oils to olefins and chemicals remains a challenge at industrial scale, mainly due to difficult upgrading step [50].

Vegetable oils, animal fats or triglyceride based biomass residues have relatively low oxygen content (≤ 10 wt. %) compared to lignocellulosic bio oils and thus can be easier processed in a milder hydrotreatment process. Particular examples of bio oils suitable for mild HDO upgrading are palm oil and crude tall oil from coniferous wood pulping [51]. Hydrotreatment of vegetable oils has been performed in commercial scale for production of renewable diesel and jet fuels over the last two decades [52]. Hydro-treatment of triglyceride vegetable oils results in renewable naphtha and propane, which can be subjected to steam cracking and PDH process, respectively. Resulting green ethylene and propylene can then be used for PE and PP production, as has been demonstrated in commercial scale [53, 54].

Advantage of hydrotreated bio oils as a feedstock is the possibility to use existing infrastructure such as cracker and PDH plants for the green olefin production. Vegetable oil production volume is 200 Mt as of 2021 [55], and a hypothetical conversion of an entire olefin industry to such feedstock would cause enormous supply–demand imbalance, likely leading to increased competition with the food value chain and deforestation [56].

Lignocellulosic bio oils from nonedible biomass (fast pyrolysis and catalytic fast pyrolysis oils, hydrothermal

liquefaction oil) are becoming increasingly available but still represent a major challenge from the catalytic upgrading (HDO) standpoint. Additional important consideration is availability of low carbon hydrogen, necessary for the hydroprocessing of bio oils. Thermal decomposition of methane is a suitable technology to provide clean “turquoise” hydrogen when available renewable power is not sufficient to fulfill the “green” hydrogen demand [57]. Methane pyrolysis splits CH_4 directly into its components, i.e., hydrogen and amorphous carbon thereby avoiding direct CO_2 emissions associated with other hydrogen types, such as coal gasification (brown) or steam methane reforming (grey) [58, 59].

A combination of technical challenges, feedstock availability and limited economic profitability suggest that “green” olefins will likely remain a minor part of the olefin portfolio in the forthcoming decades, albeit some growth can be anticipated. Technical feasibility of lignocellulosic oils conversion to olefins and chemicals remains to be demonstrated at industrial scale, while gasification and ethanol routes cannot compete with grey olefins economically. Vegetable oils and fats represent a growing segment with high technical maturity, however existing feedstock base and availability of low carbon hydrogen will need to undergo massive transformation to allow for substantial growth. To date, no “renewable content directive” exists for polyolefins to allow for additional stimulus for the growth of green PO segment.

3 Emerging technologies

3.1 Plastic recycling (pink route)

Plastic pollution and the carbon footprint of plastic value chain are two major societal drivers for increasing the circularity of polyolefins [60]. The full extent of societal and environmental aspects of plastic pollution is outside the scope of this review and the reader can be addressed to some recent publications [61]. Herein, we consider chemical recycling of polyolefins and overall plastic waste in the context of providing alternative feedstock for the olefin manufacture.

The recycling rate for plastics in US was as low as 9% in 2018, according to EPA, while certain products had higher recycling rates, such as PET bottles and jars at 29%, and HDPE natural bottles at 29% [62]. As part of its plastics strategy adopted in 2018, the European Commission has set the goal of at least 50% of all plastic packaging waste to be recycled by 2025, and then 55% by 2030. This is a combination of mechanical and chemical recycling, meaning that later is up to one third of total. It must be

pointed out that mechanical recycling, while not in the focus of this account, is estimated to contribute positively to the carbon footprint reduction of the plastic value chain [63].

Chemical recycling of plastics allows to transform them into low molecular weight products which can then be further upgraded to monomers to produce virgin quality polymer resins. Thermochemical processes based on pyrolysis and gasification are the most mature technologies in the field which are still under active development [64].

At present, advanced thermo-chemical recycling of polyolefins still lacks the optimal process design and control over complex depolymerization kinetics to effectively target tailored products and/or selected chemicals. An on-purpose production of pyrolysis oils, light gases and waxes can, to a certain extent be optimized in cases of pyrolysis technologies [65]. Multiple petrochemical producers are currently establishing alliances with technology providers and investing in pyrolysis technology, to build pilot and demonstration scale (below 100 kt/a) plants [66–68]. Some (presumably, limited volume) commercial product launches have already been announced with mass balance approach used to calculate the recycled plastic content in the final product [69]. In all cases, production of pyrolysis crude which needs to be further processed to yield the monomers is targeted.

Direct, thermochemical conversion of polyolefins to respective monomers could be an attractive solution eliminating the need of upgrading or cracking. However monomer yields reported for pyrolysis and catalytic pyrolysis of polyethylene or polypropylene are typically quite modest [70] with some notable exceptions reported for small-scale low residence time fluidized bed pyrolysis of HDPE [71] and LDPE [72]. Some simulation results indicate that it could be possible to produce up to 49% and 34% wt of ethylene and propylene respectively at 850 °C [73], however such selectivities are yet to be achieved experimentally.

Hydrothermal depolymerisation can be considered a special case of pyrolysis approach. The process is conducted in the presence of water, which acts as a reactant, catalyst and solvent and has been reported for supercritical [74] as well as low pressure [75] configurations. Low char formation and high liquid yields were reported. First commercial-sized plant using hydrothermal technology has been announced to come on stream in 2025 [76]. Available results indicate that production of pink olefins from hydrothermal crude from plastic waste would still require steam cracking to obtain olefins.

As discussed in the previous section, gasification combined with MTO or FT process can be applied for production of green olefins from biomass. The same approach can

be applied to the mixed plastic waste. Gasification converts mixed plastic waste into gases such as CH₄, H₂, CO and CO₂ via high temperature reaction with steam, CO₂, and/or limited amount of oxygen. Gasification is an energy intensive process as it requires a temperature above 700 °C [77]. The resulting syngas needs to be cleaned and conditioned to remove acid gases and impurities, before being compressed and sent to either methanol or FT synthesis reactor. In some cases the syngas needs to undergo a water–gas shift (WGS) reaction to optimize the H₂/CO ratio for synthesis [78] When plastic waste is co-processed with biomass, the resulting syngas has optimal composition, thus simplifying the system configuration and reducing the projected costs [79]. To our knowledge, no demonstration scale project following gasification-synthesis approach to polyolefin or plastic recycling have been launched yet.

In summary, plastic recycling (pink) path to olefins is under dynamic and rapid development at the moment, with pyrolysis technologies in the most advanced stage. Strong interest and commitment from the industrial players along with growing regulatory pressure will ultimately result in broader adoption of technology. At the same time, further development of thermochemical technologies towards improved yields and selectivities and lower process costs is still necessary. Available estimations indicate that pink olefins have generally higher production costs compared to grey olefins, however the difference is not prohibitively high [80]. Pre-treatment of complex post-consumer plastic waste streams containing various polymers types, halogens and metal residues still represents a number of technical challenges to be solved before deploying at full industrial scale [64]. Pyrolysis and gasification of complex mixed feeds may also result in formation of polyaromatic hydrocarbons, nitrogen and sulfur oxides, HCN and dioxins, among many other toxic compounds of high concern [64].

Impact of plastic recycling on carbon intensity of olefin manufacture is discussed in the final subchapter.

3.2 Role of CCS (Carbon capture and storage) (purple) and P2X (blue) technologies.

CCS means carbon capture and storage, the process by which carbon dioxide is captured from a point source and stored on site or often off site – for example, at a depleted gas or oil field, or other geological formation. Sequestered carbon dioxide is expected to stay underground without significant release to the atmosphere. CCS is considered a viable option in many scenarios regarding the petrochemical industry [81]. It is therefore of interest to consider the impact of CCS on manufacture of either “brown” or “grey” olefins. Analysis of Chinese coal-to olefins

processes showed that emission reduction up 30% can be expected with implementation of CCS [24]. However there is presently no centralized plan for implementation of CCS in Chinese olefin industry, and the current CCS capacity available in the country is about 2 Mt CO₂ per annum [82]. Global capacity of CCS as of 2021 is estimated to be 40 Mt by the IEA [83]. CCS deployment has been relatively slow to gain traction as multiple projects around the world have been hit by technical issues and cost overruns. Accelerated deployment and scale-up of CCS technologies would likely require creation of investment incentives, CO₂ transportation and storage infrastructure and clarification of regulatory and policing issues [84]. Before such policies and

incentives are created, no substantial impact of CCS on olefin production can be expected.

In contrast to CCS, Carbon Capture and Utilization (CCU) technologies create possibilities to re-use carbon emitted as carbon dioxide and re-introduce it into carbon value chains. The concept of carbon reuse economy, utilizing CCU integrated with direct air capture (DAC) and bioenergy (BE) technologies is the approach leading to carbon-neutral or carbon-negative fuels and chemicals, including olefins [85].

Renewable electricity used for generation of low carbon hydrogen is a key ingredient in transforming CO₂

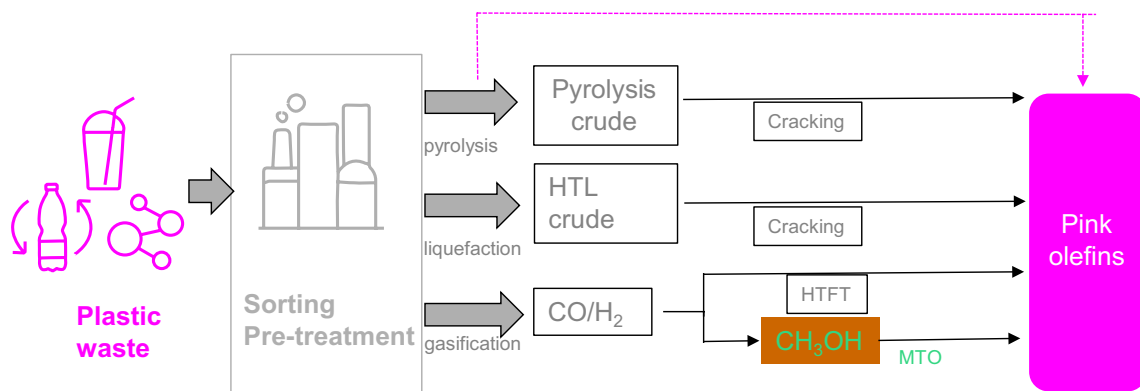


Fig. 4 Main conversion paths for waste plastic based pink olefins

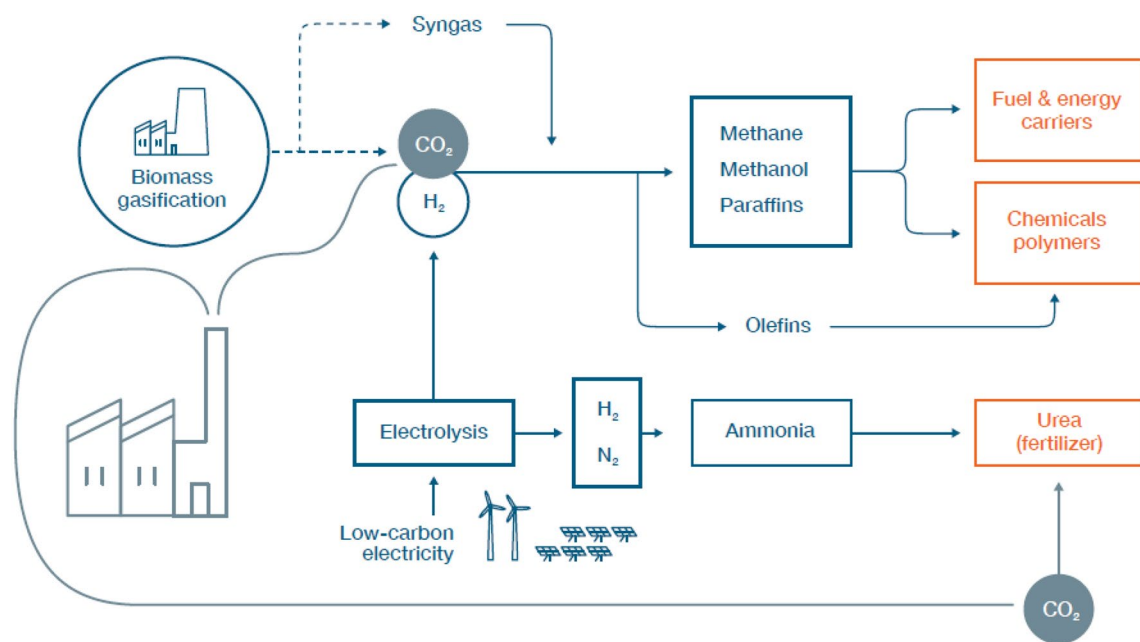


Fig. 5 P2X chemical paths to chemicals, and energy carriers including “blue” olefins. Scheme from ref 85

to chemicals via Power-to-X approach (Fig. 5). Most of the processes depicted in Fig. 4 are developed to a high Technology Readiness Level (TRL), however commercialisation has been very slow due to the lack of attractive business cases. Growing availability in renewable electric power as well as advances in electrolysis technology (including high temperature co-electrolysis of CO₂ and water) may speed up the development. Carbon Recycling International has been operating demonstration Power-to-X methanol plant in Iceland (4kt/a) since 2011, transforming CO₂ emissions from geothermal power plant to renewable methanol [86]. Larger scale renewable methanol plant is planned for construction in China [87] while several European projects on commercial scale methanol production are pending [88, 89]. None of the renewable methanol projects explicitly mentions olefins as a planned downstream product, however blue olefins can certainly be produced from renewable methanol as MTO technology is readily available.

Alternatively, HTFT route from CO₂ and renewable H₂ can be taken to produce light olefins, as proposed and tested in development project BECCU, currently run by VTT and partners [90].

Several biotechnical conversion routes from CO₂/CO and renewable H₂ were developed and brought to commercial scale to complement chemical paths depicted in Fig. 5. Fermentation processes are advantageous over FT/methanol conversion routes due to low sensitivity to impurities and syngas composition, thus deep syngas cleaning and H₂/CO ratio adjustment is not necessary [91]. Enzymatic conversions are run at ambient or close to ambient conditions, thus high pressure/high temperature reactors are not needed. However the disadvantage of fermentation processes is a low volumetric efficiency, thus extra attention needs to be paid to reactor design [92]. Typical products of syngas fermentation are ethanol/acetic acid or longer chain alcohols such as butanol and hexanol, depending on the type of enzymes used [91]. Recent project by LanzaTech, Total and l'Oreal was a first commercial scale PE packaging solution with carbon originating from industrial CO₂. CO₂ was converted to ethanol with Lanza's proprietary fermentation platform, followed by ethanol dehydration to yield polymerisation grade ethylene [93].

Economic considerations are crucial when considering potential scalability of the technology. Cost analysis calculations performed by VTT in 2017 showed that power-to-olefins approach via MTO is characterized by higher production costs of up to 2000 Eur/t for blue olefins which is roughly twice the price of fossil-based light olefins. To satisfy the global demand (ca 200 Mt/a) of light olefins through Power-to-X route, 644 GW of renewable electric power and 924 Mt/a CO₂ (3% of annual

global emissions) would be required [94, 95]. As of 2021, in most cases the production of green hydrogen, e-fuels and e-chemicals (such as methanol) still cannot directly compete with fossil based production routes due to high capital and operational costs [96].

In summary, despite the exciting emission-saving potential of Power-to-X concepts, broader adoption would require additional economic incentives (additional carbon tax, government grants for capital expenditures) as well as further deployments and technical developments in renewable energy and hydrogen production and process integration.

4 Comparison of alternative solutions

Carbon emissions are directly related to the conversion process efficiency and secondary to means of carbon capture storage or utilization. Fossil carbon content can be reduced by means of utilization of bio feedstock and applying recycling. The latter does not influence fossil carbon content in the product as such, but does reduce the need of fossil feedstock to supply the needed amount of PO product. General concepts to minimize carbon emissions and fossil carbon contents in olefins are presented in Fig. 6. Bio replacement path (green) is based on all-renewable carbon. Carbon emission free energy and hydrogen (blue) is result of electrification of chemical process. Carbon loss minimization (grey) reflects to recycling of plastic waste and more efficient operation of cracker such as applying BAT. Finally carbon emission capture (purple) processes can be applied to either of routes for olefin manufacture, allowing to lower final carbon footprint.

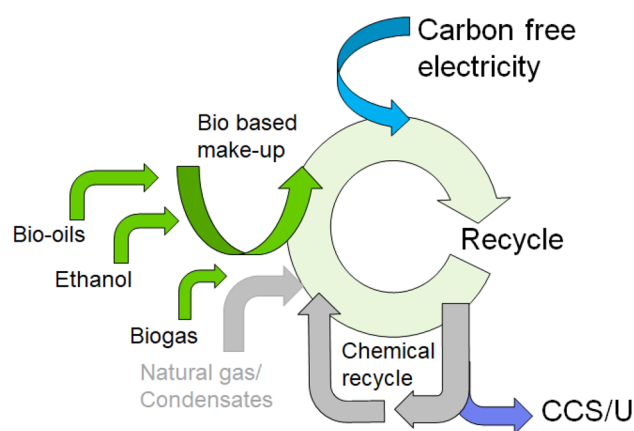


Fig. 6 Conceptual paths to minimum carbon emissions and fossil carbon contents in olefins: bio replacement (green), carbon emission free energy (blue), carbon loss minimization (grey) and carbon emission capture (purple)

Carbon dioxide emissions for different routes of olefin production have been reported earlier in several studies and compilations [1, 97, 98]. We have selected several important cases of olefin production, representing all six types of feedstock, are compared carbon dioxide emissions associated with each case (Table 1). Single illustrative values for the CO₂ emissions as well as energy demand are given to provide a comparative overview. The reader is addressed to the referenced studies for the details and methodology of LCA analyses which may differ from one study to another. For table entries, first column is the fossil carbon intensity of raw material only, energy describes the energy intensity of olefin conversion process, and “total” is sum of all fossil-based CO₂ emissions at gate as the authors have performed own assessment calculations.

Traditional naphtha steam cracker is based on high-energy consumption, especially in pyrolysis process. The process has been improved continuously over the decades and best available technology (BAT) is 7 to 12% more efficient than that of contemporary applied technology in average. Main contributor in conversion is feedstock, where gas condensates are some 10% units more efficient. “Brown” coal-to olefins route is clearly most emission-intensive, independent of the primary conversion technology. The use of this route should ideally be discouraged by additional carbon taxes or mandatory CCS implementation. Implementation of CCS can substantially improve the situation, based on simulation data [24].

Several comparisons show that bio based feed stock can be markedly high in carbon dioxide emission, even if the emissions are dominantly biogenic [100]. Bio-based materials emissions are related to fertilizers, transportation, and various energy demanding process steps. When considering total carbon emission profile of sugarcane derived ethylene via ethanol dehydrogenation, cradle-to-gate values reported in the literature vary significantly. Provided net emission values range from highly carbon negative [99] to slightly carbon negative [100] to net positive [101] and highly net positive [101], as different authors took e.g. fertilizer production and energy supply for alcohol dehydrogenation into account very differently. When most realistic scenario of bioethanol-to-ethylene is considered, some 35% of biogenic carbon is present in the overall emissions, and total carbon emissions are 45% lower than traditional grey naphtha-based steam cracking process.

Hydrodeoxygenated (HDO) bio-oils are possible feedstock for steam cracker, where the main additional factor affecting carbon emissions is the source of hydrogen used for oxygen removal. The hydrogen can come from the cracker itself, and could thus be biogenic. More efficient alternatives from the energy balance standpoint are methane pyrolysis with carbon free energy, but similarly also carbon-free electric cracker provides low carbon emission

hydrogen. In general, one can conclude that commercially viable “green” polyolefins are 35–45% less carbon intensive compared to “grey” benchmarks as evident from the examples in Table 1. MTO from cellulose pulping side streams black liquor is somewhat more attractive than ETE, with carbon emissions 55% lower than traditional SC naphtha process.

Detailed LCA for the scenario of plastic pyrolysis applied to sorted recycled plastic followed by steam cracking has been reported by BASF corporation [102]. Pyrolysis and steam cracking have major contribution to the process emissions, resulting in 3000 kg CO₂/t ethylene which is higher compared to the production of fossil-based ethylene. A “differential credit” approach is taken to consider also incineration of plastic waste as a base scenario, which would account for an additional 6000 kg CO₂/t ethylene emission as a part of plastic lifecycle. In this regard, chemical recycling is producing ca 50% lower emission vs virgin “grey” olefins production via naphtha steam cracking. Presently available technologies for both pyrolysis and steam cracking were considered in the study. One can envision that further emission reduction would be possible with e.g. electrification of steam cracking and pyrolysis, as discussed in the previous sections.

In gasification/ Fischer–Tropsch (FT) process there is a possibility to apply mixed hydrocarbon raw material, including plastic waste, to produce either naphtha or olefins directly. Later alternative is essentially more efficient, than route where first paraffins are formed from synthetic gas via LTFT and are subjected to steam cracking to produce olefins. Most efficient is a direct HTFT to olefins, when feedstock is paraffin-like polyolefin plastics. Bio feedstock, rich with oxygen, is less efficient and leads to pronounced carbon dioxide emissions. Later can be controlled by means of carbon capture followed by storage or utilization. This seems to reduce carbon emission by some 15%. Utilization of plastic waste in FT provides similar benefits as ethanol to olefin process and with carbon capture 25% better than ETE, which is 60% better than traditional naphtha cracking.

Power-to-X approaches have highest potential to reach carbon neutrality. Dechema report estimates emissions of CO₂-based methanol via direct air capture to be of ca -0.67 t CO₂/ t Methanol [14]. Process-related CO₂ emissions of a standard MTO process are estimated at 0.5 t CO₂/t olefin. Since about 2.8 t of methanol would be required to produce 1 t of olefins, total net cradle-to-gate emissions of ca -1.5 t CO₂/t olefin would be associated to production of blue olefins. More comprehensive cradle-to-grave LCA analysis by Rosental et al. [103] considers end of life of the olefins and indicates slightly positive net carbon emissions, which is still 88–95% lower than that of a fossil-based feedstock [103]. Such improvement comes

Table 1 Comparison of carbon intensity of alternative paths for olefin production

Route	Feedstock	Feedstock O/C	Primary conversion process	Comments	Fossil CO ₂ , kg/t	Energy consumed CO ₂ /kg/t	Processing total CO ₂ /Kg/t	Total CO ₂ /t	Ref
Brown	Coal	0.001	HTFT		6100	1760	2200	8300	[104]
Brown	Coal	0.001	MTO		6800	1500	1875	8650	[105]
Grey	Naphtha	0.0001	Steam cracking		2900	1063	1635	4535	[9]
Grey	Naphtha	0.0001	Steam cracking, BAT		2900	840	1063	3863	[9]
Grey	Condensate	0.0005	Steam cracking, BAT		2800	818	1062	3392	–
Grey	Naphtha	0.0001	Electro cracking	Renewable electricity	2900	200	328	3228	–
Green	Ethanol-Corn	0.57	Dehydration	Fermentation	158	1625	1816	2680	[106]
Green	Ethanol-Sugarcane	0.57	Dehydration	Fermentation	6	1472	1508	2528	[101]
Green	Palm oil	0.08	Stream cracking	Grey H ₂ for HDO	2120	1027	1533	3653	[107]
Green	Tall oil	0.06	Steam cracking	Turquoise H ₂	740	991	1436	2142	[108]
Green	Tall oil	0.06	E-cracking	Turquoise H ₂	740	200	328	1068	[103]
Green	Black liquor	0.16	MTO	Gasification/methanol	540	1300	1625	2165	
Purple	Coal CCS	0.001	MTO		800	1700	2125	2925	[24]
Pink	Plastic waste		HTFT	Gasification	360	1760	2200	2560	–
Pink	Plastic waste		steam cracking	Pyrolysis	–	–	–	3013 ^a	[108]
Blue- P2X	CO ₂ , DAC	2.67	MTO	DAC, HTCOE	– 2000		500	– 1500	[14]
Brown	Coal	0.001	HTFT		6100	1760	2200	8300	[104]
Brown	Coal	0.001	MTO		6800	1500	1875	8650	[105]
Grey	Naphtha	0.0001	Steam cracking		2900	1063	1635	4535	[9]
Grey	Naphtha	0.0001	Steam cracking, BAT		2900	840	1063	3863	[9]
Grey	Condensate	0.0005	Steam cracking, BAT		2800	818	1062	3392	–
Grey	Naphtha	0.0001	Electro cracking	Renewable electricity	2900	200	328	3228	–
Green	Ethanol-Corn	0.57	Dehydration	Fermentation	158	1625	1816	2680	[106]
Green	Ethanol-Sugarcane	0.57	Dehydration	Fermentation	6	1472	1508	2528	[101]
Green	Palm oil	0.08	Stream cracking	Grey H ₂ for HDO	2120	1027	1533	3653	[107]
Green	Tall oil	0.06	Steam cracking	Turquoise H ₂	740	991	1436	2142	[108]
Green	Tall oil	0.06	E-cracking	Turquoise H ₂	740	200	328	1068	[103]
Green	Black liquor	0.16	MTO	Gasification/methanol	540	1300	1625	2165	
Purple	Coal CCS	0.001	MTO		800	1700	2125	2925	[24]
Pink	Plastic waste		HTFT	Gasification	360	1760	2200	2560	–
Pink	Plastic waste		steam cracking	Pyrolysis	–	–	–	3013 ^a	[108]
Blue- P2X	CO ₂ , DAC	2.67	MTO	DAC, HTCOE	– 2000		500	– 1500	[14]

^a Total processing and energy impacts, derived from value 3348 kg/t PE reported in ref 108 minus 10% attributed to polymerization process

Table 2

Color	Raw material	Primary conversion	TRL ^a	Production costs ^b	CO ₂ emissions	Opportunities and development needs	Outlook	References
Grey	Naphtha, NG	Steam cracking, PDH	9	Benchmark	Benchmark	Mid term: improving cracker efficiency, partial incorporation of green and pink feedstock Long term: E-cracking	Major path for olefin production for next 10–20 years, with gradually growing recycled and renewable feedstock fractions	–
Brown	Coal	HFT, MTO	9	+ -20% ^c	+ 100–200%	Incorporation of CCS/CCU. Most preferably discouraged with carbon tax	Highly dependent on national regulatory policies	[109]
Green	Vegetable oils, fats	HDO, cracking	8	+ 20–40%	– 30%	Growing availability of bio-naphtha	Moderate growth, limited by feedstock availability	[110]
	Bioethanol	ETE	8	+ 30–50%	– 40%	Availability of G2 bioethanol	Limited growth due to unfavorable process economics	[32]
Pink	Lignocellulosic residues	Gasification with HTFT/MTO or Liquefaction/HDO then cracking	4–6	+ 20–40%	– 30–50%	Major technical challenges still to be solved, robust HDO upgrading of lignocellulosic bio oils to be developed. Economically viable gasification/synthesis concept to be developed	First-of-a-kind demo plant within next 10 years	[95]
			7–8	+ 10–30%	– 30%	Robust pre- and post-treatment options for mixed and contaminated plastic waste streams. Improved process yield and selectivity	Continuous growth in next decades, pink (poly)olefins may reach 5–10% of PO market	[80, 107]
Purple	Coal	Gasification and FTO/HTFT	5–6	+ 20–40%	– 40%	Technology maturity and economic viability need to be improved	First demo plants within next 10 years	[111]
			7	+ 10–40%	– 20%	Relatively mature technology, would require systemic infrastructural changes to enable capture transport and storage	Limited growth only in case of major policy changes	[24]
Blue	CO ₂ , point sources	(co)Electrolysis, RWGS, HTFT or MTO	4–6	+ 100%	– 90%	Technology maturity needs improvement, price of low carbon electricity and renewable hydrogen will be major economic factor	Several industrial demo cases at TRL 6–7 in the next decade, no commercial volumes	[94, 95, 105]

^aTechnology readiness level, value given for the process step(s) of lowest technical maturity. ^b cost estimate ranges based on available literature references ^c highly dependent on oil price, see reference 111.

at a price of an enormous need in renewable energy, as energy needed for production of “blue” olefins is ca twice the energy needed for the “grey” benchmark [108].

Comparative overview of six principal paths for olefin production is presented in Table 2. While there are seemingly multiple options to produce olefins, the most technically mature fossil-based “grey” olefins and polyolefins will likely continue to dominate the markets in foreseeable future. Pink olefins are clearly on their way to transition from “emerging” to “commercial” status.

5 Conclusions

While multiple options to reduce carbon footprint of olefin production exist in the form of relatively mature technologies, we expect that traditional, “grey” fossil based olefins will dominate the markets for next 2–3 decades which is in line with other projections in the literature [1]. Introduction of BAT in naphtha cracking and utilization of condensates may reduce carbon emissions by 20% compared with standard olefin production. Transition to green feedstocks such as ethanol to ethylene route will bring substantial benefit in CO₂ emission reduction of up to 45%, however broader implementation will likely be hampered by economical disadvantages Vs conventional “grey” route. The share of “green” olefins will grow over next decades, however major technical breakthroughs in biomass gasification or lignocellulosic bio oils upgrading will be necessary, as availability of vegetable oil feedstock is limited. Plastic waste recycling does not markedly reduce carbon emissions, but could reduce fossil feedstock utilization for 25 to 55%. We expect that “pink” olefins produced from plastic waste will experience a strong growth over next decade as manifested by strong commitment from the industry. Ultimate emission reduction by 80–90% can be achieved via adoption of Power-to-X technologies which at present are not economically competitive with fossil based routes without additional carbon taxes and governmental incentives. Olefins and polyolefins are going to remain carbon-positive material in the next 3–4 decades. However PO's contribution to lowering emissions remains significant due to indispensable functions such as energy transport and storage, food chain security and low carbon mobility. This solid net negative effect fully justifies and will further strengthen polyolefins' role in future sustainable society.

Funding This work was partially funded by Academy of Finland Plastic Hero project.

Declarations

Conflict of interest There are no conflicts of interest to declare.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Amghizar I, Vandewalle LA, Van Geem KM, Marin GB (2017) New trends in olefin production. *Engineering* 3:171–178. <https://doi.org/10.1016/J.ENG.2017.02.006>
2. Nakajima H, Dijkstra P, Loos K (2017) The recent developments in biobased polymers toward general and engineering applications: Polymers that are upgraded from biodegradable polymers, analogous to petroleum-derived polymers, and newly developed. *Polymers* 9:1–26. <https://doi.org/10.3390/polym9100523>
3. Chen, J (2013) Global markets for polyolefin resins, PLS052. BCC research report.
4. Gahleitner M (2020) Editorial corner – a personal view are polyolefins outdated? *Express Polym Lett* 14:704. <https://doi.org/10.3144/expresspolymlett.2020.57>
5. Laurikko J et al (2020) National Hydrogen Roadmap for Finland. Business Finland https://www.businessfinland.fi/4abb35/globalassets/finnish-customers/02-build-your-network/bioeconomy--cleantech/alykas-energia/bf_national_hydrogen_roadmap_2020.pdf Accessed 04.01.2022.
6. Tullo AH (2021) Is ammonia the fuel of the future? *Chemical & Engineering News*, 99:20–22 <https://cen.acs.org/business/ Petrochemicals/ammonia-fuel-future/99/i8> Accessed 15.12.2021
7. Maia JG et al (2018) Process modeling and simulation of an industrial-scale plant for green ethylene production. *Ind Eng Chem Res* 57:6401–6416. <https://doi.org/10.1021/acs.iecr.8b00776>
8. Wiley Critical Content - Petroleum Technology, Volume 2 (2007). John Wiley & Sons, Inc., New Jersey.
9. Ren T, Patel M, Blok K (2006) Olefins from conventional and heavy feedstocks: energy use in steam cracking and alternative processes. *Energy* 31:425–451. <https://doi.org/10.1016/j.energy.2005.04.001>
10. Ren T, Patel MK, Blok K (2008) Steam cracking and methane to olefins: energy use, CO₂ emissions and production costs. *Energy* 33:817–833. <https://doi.org/10.1016/j.energy.2008.01.002>
11. Benchaita T (2013) Greenhouse Gas Emissions from New Petrochemical Plants; Technical Note No. IDB-TN-562; Inter-American Development Bank: Washington, DC, USA. <https://publications.iadb.org/publications/english/document/Greenhouse-Gas-Emissions-from-New-Petrochemical-Plants-Background-Information-Paper-for-the-Elaboration-of-Techn>

- ical-Notes-and-Guidelines-for-IDB-Projects.pdf Accessed 04.01.2021
12. Speight J (2001) Chemical process and design handbook. McGraw-Hill Professional, New Jersey
 13. Pretz M, Fish B, Luo L, Stears B (2017) Shaping the future of on-purpose propylene production. *Hydrocarb Process* 96:29–36
 14. Bazzanella AM, Ausfelder F (2017) Low carbon energy and feedstock for the European chemical industry. DECHEMA, Gesellschaft für Chemische Technik und Biotechnologie e.V. https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry.pdf accessed 01.05.2021
 15. Chan Y et al (2019) Industrial Innovation: Pathways to decarbonisation of Industry. Part 1: Technology Analysis. Fraunhofer Institute for Systems and Innovation Research (ISI), ICF Consulting Services Limited. https://ec.europa.eu/clima/system/files/2019-03/industrial_innovation_part_1_en.pdf [Accessed 01.11.2021]
 16. Koester V (2019) BASF – working intensely on eco-efficiency. *ChemistryViews*. <https://doi.org/10.1002/chemv.201900004>
 17. Accelerating electrification with the “Cracker of the Future” Consortium (2021). Brightlands Chemelot Campus. https://www.brightlands.com/en/brightlands-chemelot-campus/nieuws/accelerating-electrification-cracker-future-consortium#_ftnref1 accessed 04.01.2021.
 18. Coolbrook starts work on world's first sustainable naphtha cracker (2021). <https://coolbrook.com/news/2021/coolbrook-starts-work-on-worlds-first-sustainable-naphtha-cracker/> accessed 18.10.2021
 19. Amghizar I, Dedeyne JN, Brown DJ, Marin GB, Van Geem KM (2020) Sustainable innovations in steam cracking: CO₂ neutral olefin production. *Reaction Chem Eng* 5:239–257. <https://doi.org/10.1039/c9re00398>
 20. Tullo AH (2020) Petrochemical makers look ahead to an uncertain decade *Chemical & Engineering News*, 98:16–18. <https://cen.acs.org/business/petrochemicals/Petrochemical-makers-look-ahead-uncertain/98/i10>
 21. Tian P, Wei Y, Ye M, Liu Z (2015) Methanol to olefins (MTO): From fundamentals to commercialization. *ACS Catal* 5:1922–1938. <https://doi.org/10.1021/acscatal.5b00007>
 22. Chang CD, Silvestri AJ (1977) The conversion of methanol and other O-compounds to hydrocarbons over zeolite catalysts. *J Catal* 47:249–259. [https://doi.org/10.1016/0021-9517\(77\)90172-5](https://doi.org/10.1016/0021-9517(77)90172-5)
 23. China's Baofeng Soars on Plan to Build USD10.3 Billion Coal-to-Olefins Plant (2021) <https://www.yicai.com/news/china-baofeng-soars-on-plan-to-build-usd103-billion-coal-to-olefins-plant> Accessed 15.04.2021
 24. Xu Z, Fang C, Ma T (2020) Analysis of China's olefin industry using a system optimization model considering technological learning and energy consumption reduction. *Energy*. <https://doi.org/10.1016/j.energy.2019.116462>
 25. Demirbas, A (2008) Biodiesel - A Realistic Fuel Alternative for Diesel Engines. Springer – Verlag, London.
 26. Wang X, Economides M (2009) Advanced natural gas engineering. Gulf Publishing Company, Houston
 27. Higman C, Van der Burgt M (2008) Van der Burgt M (2008) Gasification, 2nd edn. Elsevier, Amsterdam
 28. Duvenhage DJ, Shingles T (2002) Synthol reactor technology development. *Catal Today* 71:301–305. [https://doi.org/10.1016/S0920-5861\(01\)00456-4](https://doi.org/10.1016/S0920-5861(01)00456-4)
 29. Kjellin M, Johansson I (2010) Surfactants from renewable resources (Wiley Series in Renewable Resources). Wiley, Chippenhams
 30. Hannula I, Arpiainen V (2015) Light olefins and transport fuels from biomass residues via synthetic methanol: performance and cost analysis. *Biomass Convers Biorefin* 5:63–74. <https://doi.org/10.1007/s13399-014-0123-9>
 31. Rass-Hansen J, Falsig H, Jørgensen B, Christensen C (2007) Bioethanol: fuel or feedstock? *J Chem tech biotech* 82:329–333. <https://doi.org/10.1002/jctb.1665>
 32. Mohsenzadeh A, Taherzadeh ZA (2017) Bioethylene production from ethanol: a review and techno-economical evaluation. *ChemBioEng Rev* 4:75–91. <https://doi.org/10.1002/cben.201600025>
 33. <https://www.braskem.com.br/imgreen/bio-based-en> accessed 05.01.2021
 34. Going green: Use of Braskem's green polyethylene exceeds 150 brands worldwide (2019) <https://www.packaginginsights.com/news/going-green-use-of-braskems-green-polyethylene-exceeds-150-brands-worldwide.html> accessed 14.07.2021
 35. Carvalho L, Lundgren J, Wetterlund E, Wolf J, Furusjö E (2018) Methanol production via black liquor co-gasification with expanded raw material base – techno-economic assessment. *Appl Energy* 225:570–584. <https://doi.org/10.1016/j.apenergy.2018.04.052>
 36. Simell P, Hannula I, Tuomi S, Nieminen M, Kurkela E, Hiltunen I, Kaisalo N, Kihlman J (2014) Clean syngas from biomass—process development and concept assessment. *Biomass Conv Biorefin* 4:357–370. <https://doi.org/10.1007/s13399-014-0121-y>
 37. Frilund C, Tuomi S, Kurkela E, Simell P (2021) Small- to medium-scale deep syngas purification: biomass-to-liquids multi-contaminant removal demonstration. *Biomass Bioenergy* 148:106031. <https://doi.org/10.1016/j.biombioe.2021.106031>
 38. Jasper S, El-Halwagi MM (2015) A techno-economic comparison between two methanol-to-propylene processes. *Processes* 3:684–693. <https://doi.org/10.3390/pr3030684>
 39. Gogate MR (2019) Methanol-to-olefins process technology: current status and future prospects. *Pet Sci Technol* 37:559–565. <https://doi.org/10.1080/10916466.2018.1555589>
 40. Lu Y, Yan Q, Han J, Cao B, Street J, Yu F (2017) Fischer-Tropsch synthesis of olefin-rich liquid hydrocarbons from biomass-derived syngas over carbon-encapsulated iron carbide/iron nanoparticles catalyst. *Fuel* 193:369–384. <https://doi.org/10.1016/j.fuel.2016.12.061>
 41. Maier S, Tuomi S, Kihlman J, Kurkela E, Dietrich RU (2021) Techno-economically-driven identification of ideal plant configurations for a new biomass-to-liquid process – a case study for Central-Europe. *Energy Convers Manag* 247:114651. <https://doi.org/10.1016/j.enconman.2021.114651>
 42. Onel O, Niziolek AM, Elia JA, Baliban RC, Floudas CA (2015) Biomass and natural gas to liquid transportation fuels and olefins (BGTL+C2-C4): Process synthesis and global optimization. *Ind Eng Chem Res* 54:359–385. <https://doi.org/10.1021/ie503979b>
 43. Zámotný P, Bělohav Z, Šmidrkal J (2012) Production of olefins via steam cracking of vegetable oils. *Resour Conserv Recy* 59:47–51. <https://doi.org/10.1016/j.resconrec.2011.03.007>
 44. Pyl SP, Dijkmans T, Anthonykutty JM, Reyniers MF, Harlin A, Van Geem KM, Marin GB (2012) Wood-derived olefins by steam cracking of hydrodeoxygenated tall oils. *Bioresour Technol* 126:48–55. <https://doi.org/10.1016/j.biortech.2012.09.037>
 45. Gong F et al (2011) Selective conversion of bio-oil to light olefins: Controlling catalytic cracking for maximum olefins. *Bioresour Technol* 102:9247–9254. <https://doi.org/10.1016/j.biortech.2011.07.009>
 46. Bezergianni S, Dimitriadis A, Kikhtyanin O, Kubička D (2018) Refinery co-processing of renewable feeds. *Prog Energy Combust* 68:29–64. <https://doi.org/10.1016/j.pecs.2018.04.002>
 47. Ardiyanti AR, Khromova SA, Venderbosch RH, Yakovlev VA, Heeres HJ (2012) Catalytic hydrotreatment of fast-pyrolysis oil using non-sulfided bimetallic Ni-Cu catalysts on a δ -Al₂O₃

- support. *Appl Catal B* 117:105–117. <https://doi.org/10.1016/j.apcatb.2011.12.032>
48. Mortensen PM, Grunwaldt JD, Jensen PA, Knudsen KG, Jensen AD (2011) A review of catalytic upgrading of bio-oil to engine fuels. *Appl Catal A* 407:1–19. <https://doi.org/10.1016/j.apcata.2011.08.046>
49. Zacher AH, Olarte MV, Santosa DM, Elliott DC, Jones SB (2014) A review and perspective of recent bio-oil hydrotreating research. *Green Chem* 16:491–515. <https://doi.org/10.1039/C3GC41382A>
50. Zhang S et al (2019) Liquefaction of biomass and upgrading of bio-oil: a review. *Molecules* 24:1–30. <https://doi.org/10.3390/molecules24122250>
51. Bruycker RD et al (2014) Assessing the potential of crude tall oil for the production of green base-chemicals: an experimental and kinetic modeling study. *Ind Eng Chem Res* 53:18430–18442. <https://doi.org/10.1021/ie503505f>
52. Vásquez MC, Silva EE, Castillo EF (2017) Hydrotreatment of vegetable oils: a review of the technologies and its developments for jet biofuel production. *Biomass Bioenerg* 105:197–206. <https://doi.org/10.1016/j.biombioe.2017.07.008>
53. IKEA and Neste take a significant step towards a fossil-free future (2018) Neste. <https://www.neste.com/releases-and-news/renewable-solutions/ikea-and-neste-take-significant-step-towards-fossil-free-future> accessed 30.04.2021
54. Borealis producing certified renewable polypropylene at own facilities in Belgium (2020) Borealis. <https://www.borealisgroup.com/news/borealis-producing-certified-renewable-polypropylene-at-own-facilities-in-belgium> Accessed 18.10.2021
55. Vegetable oils and fats (2021) Statista report did-21986–1 <https://www.statista.com/study/21986/vegetable-oils-and-fats-statista-dossier/> Accessed 18.10.2021
56. Pacheco P et al (2021). Deforestation fronts: Drivers and responses in a changing world. WWF, Gland, Switzerland.
57. Sanchez-Bastardo N, Schlong R, Ruland H (2020) Methane Pyrolysis for CO₂-free H₂ production: a green process to overcome renewable energies unsteadiness. *Chem Ing Tech* 92:1596–1609. <https://doi.org/10.1002/cite.202000029>
58. Muradov NZ, Veziroglu TN (2005) From hydrocarbon to hydrogen-carbon to hydrogen economy. *Int J Hydrog Energy* 30:225–237. <https://doi.org/10.1016/j.ijhydene.2004.03.033>
59. Parkinson B et al (2018) Hydrogen production using methane: techno-economics of decarbonizing fuels and chemicals. *Int J Hydrog Energy* 43:2540–2555. <https://doi.org/10.1016/j.ijhydene.2017.12.081>
60. Tenhunen A, Pöhler H. (Eds.) (2020) A Circular Economy of Plastics: A vision of redesigning plastics value chains. VTT Technical Research Centre of Finland. VTT Discussion paper DOI: <https://doi.org/10.32040/2020.978-951-38-8824-4>
61. Meijer LJJ, van Emmerik T, van der Ent R, Schmidt C, Lebreton L (2021) More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Sci Adv*. <https://doi.org/10.1126/sciadv.aaz5803>
62. Facts and Figures about Materials, Waste and Recycling. EPA publication <https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling> accessed 12.07.2021
63. Bataineh KM (2020) Life-cycle assessment of recycling postconsumer high-density polyethylene and polyethylene terephthalate. *Adv Civ Eng*. <https://doi.org/10.1155/2020/8905431>
64. Dogu O et al (2021) The chemistry of chemical recycling of solid plastic waste via pyrolysis and gasification: state-of-the-art, challenges, and future directions. *Prog Energy Combust Sci* 84:100901. <https://doi.org/10.1016/j.pecs.2020.100901>
65. Qureshi MS et al (2020) Pyrolysis of plastic waste: opportunities and challenges. *J Anal Appl Pyrolysis*. <https://doi.org/10.1016/j.jaap.2020.104804>
66. Plastic Energy Collaborates With ExxonMobil On Advanced Recycling Project In France (2021) Plastic Energy press release https://plasticenergy.com/plastic_energy_collaborates_with_exxonmobil_on_advanced_recycling_project_in_france/accessible 12.07.2021
67. ReOil: 200,000 kg of plastic waste recycled with OMV's circular economy pilot project (2020) OMV press release <https://www.omv.com/en/news/reoil-200-000-kg-of-plastic-waste-recycled-with-omv-s-circular-economy-pilot-project-> accessed 12.07.2021
68. LyondellBasell Successfully Starts Up New Pilot Molecular Recycling Facility (2020) Lyondellbasell press release <https://www.lyondellbasell.com/en/news-events/corporate-financial-news/lyondellbasell-successfully-starts-up-new-pilot-molecular-recycling-facility/> accessed 12.07.2021
69. First Henkel bottles made of chemically recycled plastic (2019) Henkel press release <https://www.henkel.com/press-and-media/press-releases-and-kits/2019-10-17-first-henkel-bottles-made-of-chemically-recycled-plastic-991126> accessed 12.07.2021
70. Miao Y, von Jouanne A, Yokochi A (2021) Current technologies in depolymerization process and the road ahead. *Polymers* 13:1–17. <https://doi.org/10.3390/polym13030449>
71. Mastral FJ, Esperanza E, García P, Juste M (2002) Pyrolysis of high-density polyethylene in a fluidised bed reactor. influence of the temperature and residence time. *J Anal Appl Pyrolysis* 63:1–15. [https://doi.org/10.1016/S0165-2370\(01\)00137-1](https://doi.org/10.1016/S0165-2370(01)00137-1)
72. Williams PT, Williams EA (1999) Fluidised bed pyrolysis of low density polyethylene to produce petrochemical feedstock. *J Anal Appl Pyrolysis* 51:107–126. [https://doi.org/10.1016/S0165-2370\(99\)00011-X](https://doi.org/10.1016/S0165-2370(99)00011-X)
73. Somoza-Tornos A et al (2020) Realizing the potential high benefits of circular economy in the chemical industry: ethylene monomer recovery via polyethylene pyrolysis. *ACS Sustain Chem Eng* 8:3561–3572. <https://doi.org/10.1021/acsschemeng.9b04835>
74. Chen WT, Jin K, Linda Wang NHL (2019) Use of supercritical water for the liquefaction of polypropylene into oil. *ACS Sustain Chem Eng* 7:3749–3758. <https://doi.org/10.1021/acsschemeng.8b03841>
75. Jin K, Vozka P, Gentilcore C, Kilaz G, Wang NHL (2021) Low-pressure hydrothermal processing of mixed polyolefin wastes into clean fuels. *Fuel* 294:120505. <https://doi.org/10.1016/j.fuel.2021.120505>
76. Teesside HydroPRS plant set to recycle all plastics (2021) <https://www.theengineer.co.uk/teesside-hydroprs-plant-set-to-recycle-all-plastics/> accessed 05.01.2022.
77. Janajreh I, Adeyemi I, Elagroudy S (2020) Gasification feasibility of polyethylene, polypropylene, polystyrene waste and their mixture: experimental studies and modeling. *Sustain Energy Technol Assess* 39:100684. <https://doi.org/10.1016/j.seta.2020.100684>
78. Speight JG (2019). Chapter 13 - Upgrading by Gasification. In: Speight JG (ed.) *Heavy Oil Recovery and Upgrading* Gulf Professional Publishing. 559–614. DOI: <https://doi.org/10.1016/B978-0-12-813025-4.00013-1>
79. Brachi P, Chirone R, Miccio F, Miccio M, Picarelli A, Ruoppolo G (2014) Fluidized bed co-gasification of biomass and polymeric wastes for a flexible end-use of the syngas: focus on bio-methanol. *Fuel* 128:88–98. <https://doi.org/10.1016/j.fuel.2014.02.070>
80. Volk R, Stallkamp C, Steins JJ, Yogish SP, Müller RC, Stapf D, Schultmann F (2021) Techno-economic assessment and comparison of different plastic recycling pathways: a German case study. *J Ind Ecol* 25:1318–1337. <https://doi.org/10.1111/jiec.13145>

81. Boulamanti A, Moya Rivera J (2017) Energy efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry. EUR 28471 EN. Luxembourg (Luxembourg): Publications Office of the European Union; 2017. JRC105767 DOI: <https://doi.org/10.2760/63030810.2760/20486>
82. The Global Status of CCS: 2021 (2021) Global CCS Institute, 2021. Australia
83. IEA (2021), About CCUS, IEA, Paris <https://www.iea.org/reports/about-ccus>
84. Turan G (2020) Are stars finally aligning for CCS in Europe? EURACTIV Media <https://www.euractiv.com/section/energy-environment/opinion/are-stars-finally-aligning-for-ccs-in-europe/> accessed 04.01.2021
85. Lehtonen J et al (2019) The carbon reuse economy: transforming CO₂ from a pollutant into a resource. VTT Tech Res Centre Finland. <https://doi.org/10.32040/2019.978-951-38-8709-4>
86. Kaw M, Benders RMJ, Visser C (2015) Green methanol from hydrogen and carbon dioxide using geothermal and/or hydro-power in Iceland or excess renewable electricity in Germany. Energy 90:208–217. <https://doi.org/10.1016/j.energy.2015.06.002>
87. Hutchins M (2020) China's 'Liquid Sunshine' project demonstrates PV powered methanol. PV magazine. <https://www.pv-magazine.com/2020/11/13/chinas-liquid-sunshine-project-demonstrates-pv-powered-methanol/>
88. Perstorp (2021) Positive feedback for Project AIR for sustainable methanol production from EU Innovation Fund https://www.perstorp.com/en/news_center/pressreleases/2021/top_scores_from_eu_innovation_fund accessed 01.04.2021
89. Fuelcellworks (2021) Wacker and Linde project for generating green hydrogen reaches next selection stage for EU funding. <https://fuelcellworks.com/news/wacker-and-linde-project-for-generating-green-hydrogen-reaches-next-selection-stage-for-eu-funding/> accessed 01.05.2021
90. BECCU project, <https://www.beccu.fi/about-beccu/> accessed 01.06.2021
91. Heijstra BD, Leang C, Juminaga A (2017) Gas fermentation: cellular engineering possibilities and scale up. Microb Cell Fact 16:1–11. <https://doi.org/10.1186/s12934-017-0676-y>
92. Stoll IK, Boukis N, Sauer J (2020) Syngas fermentation to alcohols: reactor technology and application perspective. Chem-Ing-Tech 92:125–136. <https://doi.org/10.1002/cite.201900118>
93. Lanzatech (2020) LanzaTech, Total and L'Oréal Announce a Worldwide Premiere: The Production of the First Cosmetic Packaging Made From Industrial Carbon Emissions <https://www.lanzatech.com/2020/10/27/lanzatech-total-and-loreal-announce-a-worldwide-premiere-the-production-of-the-first-cosmetic-packaging-made-from-industrial-carbon-emissions/> Accessed 04.01.2022
94. Kärki J, Vakkilainen E (2017) Screening for the most promising business cases for P2X deployment in renewable energy systems http://www.neocarbonenergy.fi/wp-content/uploads/2015/03/NCE_WP3_1st-phase_summary_final.pdf
95. Hannula I (2015) Co-production of synthetic fuels and district heat from biomass residues, carbon dioxide and electricity: performance and cost analysis. Biomass Bioenergy 74:26–46. <https://doi.org/10.1016/j.biombioe.2015.01.006>
96. Bos MJ, Kersten SRA, Brilman DWF (2020) Wind power to methanol: Renewable methanol production using electricity, electrolysis of water and CO₂ air capture. Appl Energy 264:114672. <https://doi.org/10.1016/j.apenergy.2020.114672>
97. Zhao Z, Chong K, Jiang J, Wilson K, Zhang X, Wang F (2018) Low-carbon roadmap of chemical production: a case study of ethylene in China. Renew Sust Energ Rev 97:580–591. <https://doi.org/10.1016/j.rser.2018.08.008>
98. Negri A, Ligthart T (2020) Decarbonisation options for the Dutch polyolefins industry. PBL Netherlands Environmental Assessment Agency and TNO EnergieTransitie, The Hague. <https://www.pbl.nl/en/publications/decarbonisation-options-for-the-dutch-polyolefins-industry> accessed 10.04.2021
99. Braskem (2017). I'm green™ PE Life Cycle Assessment. <http://plasticoverde.braskem.com.br/Portal/Principal/Arquivos/ModuloHTML/Documentos/1191/Life-Cycle-Assessment-v02.pdf>
100. Tsiropoulos I, Faaij APC, Lundquist L, Schenker U, Patel BJJ, MK, (2015) Life cycle impact assessment of bio-based plastics from sugarcane ethanol. J Clean Prod 90:114–127. <https://doi.org/10.1016/j.jclepro.2014.11.071>
101. Muñoz I, Flury K, Jungbluth N, Rigarlford G, Canals LM, King H (2014) Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int J Life Cycle Assess 19:109–119. <https://doi.org/10.1007/s11367-013-0613-1>
102. BASF (2020) Life cycle assessment (LCA) for ChemCycling™ <https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainable-solutions/circular-economy/mass-balance-approach/chemcycling/lca-for-chemcycling.html> accessed 05.01.2022
103. Rosental M, Fröhlich T, Liebich A (2020) Life cycle assessment of carbon capture and utilization for the production of large volume organic chemicals. Front Clim 2:1–14. <https://doi.org/10.3389/fclim.2020.586199>
104. Huang Y et al (2018) Energy use, greenhouse gases emission and cost effectiveness of an integrated high- and low-temperature Fisher-Tropsch synthesis plant from a lifecycle viewpoint. Appl Energy 228:1009–1019. <https://doi.org/10.1016/j.apenergy.2018.07.007>
105. Gao D, Qiu X, Zhang Y, Liu P (2018) Life cycle analysis of coal based methanol-to-olefins processes in China. Comput Chem Eng 109:12–118. <https://doi.org/10.1016/j.compchemeng.2017.11.001>
106. Ghanta M, Fahey D, Subramaniam B (2014) Environmental impacts of ethylene production from diverse feedstocks and energy sources. Appl Petrochem Res 4:167–179. <https://doi.org/10.1007/s13203-013-0029-7>
107. Wahyono Y (2020) Assessing the environmental performance of palm oil biodiesel production in indonesia: a life cycle assessment approach. Energies 13:3248. <https://doi.org/10.3390/en13123248>
108. Cashman SA, Moran KM, Gaglione AG (2016) Greenhouse gas and energy life cycle assessment of pine chemicals derived from crude tall oil and their substitutes. J Ind Ecol 20:1108–1121. <https://doi.org/10.1111/jiec.12370>
109. Zhang Q, Hu S, Chen D (2017) A comparison between coal-to-olefins and oil-based ethylene in China: an economic and environmental perspective. J Clean Prod 165:1351–1360. <https://doi.org/10.1016/j.jclepro.2017.06.229>
110. Little to no public insight is available on pricing and production costs of bio naphtha. Some estimates of ca 2 times cost of fossil based naphtha were published recently https://www.bkv-gmbh.de/files/bkv-neu/studien/Thermal_Processes_for_Feedstock_Recycling_of_Plastics_Waste_short.pdf. accessed 05.01.2021
111. BKV and Plastics Europe (2019) Thermal processes for feedstock recycling of plastic waste, study conducted by KIT https://www.bkv-gmbh.de/files/bkv-neu/studien/Thermal_Processes_for_Feedstock_Recycling_of_Plastics_Waste_short.pdf accessed 05.01.2021

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.