Ethylene

HIGHLIGHTS

Processes and technology status – Ethylene is one of the most important building blocks for production of a wide variety of chemicals such as polyethylene, ethylene oxide, ethylbenzene [1], [2]. Feedstocks for production of Ethylene are hydrocarbons ranging from methane to naphtha [3]. Ethylene can be produced through various routes. The main production route is by steam-cracking of hydrocarbons [4]. In fact, the main product of steam cracker is ethylene and its main by-product is propylene. The block flow diagram and process requirements of steam cracker are explained in the previous fact sheet on the Propylene production [5]. The other main routes of ethylene production are methanol-to-olefins (MTO), catalytic dehydration of ethanol, oxidative dehydrogenation of ethane, oxidative coupling of methane, and, Fischer-Tropsch synthesis [4].

Cost – Average cost of ethylene production from ethylene-propane base steam cracker is 265.49 $€_{2017}/t_{Ethylene}$[1] while it is equal to 539.82 $€_{2017}/t_{Ethylene}$[2] for the naphtha as feedstock [6]. Since 2008, the availability of low-cost ethane from shale gas has favored the use of pure steam crackers [7]. Manufacturing of ethylene from shale gas results in much lower production costs for ethylene than the conventional naphtha cracking design. However, shale gas routes impose higher costs in terms of life cycle GHG emissions [6].

Potential and barriers – High emission of carbon dioxide from steam crackers is an essential barrier in front of the main production route of ethylene while, the global demand of ethylene is likely to continue to grow even during the Covid-19 pandemic. In fact, demand for monomers going into polyethylene production is boosted by increased requirements from the packaging sector [8], [9].

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[1] 1 $€_{2017}$ = 1.13 $\$_{2017}$ [54]

[2] 300 $\$_{2017}/t_{Ethylene}$ and 610 $\$_{2017}/t_{Ethylene}$ respectively [6]

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Ethylene – Ethylene is the core chemical product of the petrochemical industry chain. Ethylene and downstream products, such as polyethylene (PE), ethylene glycol and styrene, account for about 75 percent of petrochemical products. Moreover, the scale and production technology level of ethylene production plant often determines the development of petrochemical industry at each country [10].

Process overview - Ethylene is obtained mainly from cracking of naphtha, gasoil and condensates with the coproduction of propylene, C_4 olefins and aromatics (pyrolysis gasoline) [11]. There exist other ethylene productions namely catalytic dehydration of ethanol, oxidative dehydrogenation of ethane (ODH), oxidative coupling of methane and methanol-to-olefins (MTO) [4]. Moreover, Small quantities of dilute ethylene can be obtained from methanol-to-propylene (MTP) and refinery streams [4], [11]. According to the statistics, naphtha and light olefins such as ethane based ethylene production accounts for 55% and 36.7% of the global ethylene production respectively [12]. Ethylene is the main product of steam cracker [5]. Details of the steam cracking technology, process, feed and cost requirements are explained in the previous fact sheet on the Propylene production [5]. For example, the naphtha-based steam cracker requires 2.7 tons of naphtha per one ton of ethylene production [13]. The summary of data is available in table 3 of this fact sheet as well. Requirements of MTP and MTO are, also, completely discussed at the same report, the fact sheet on the Propylene production [5]. The specific energy consumption (SEC) at MTO for ethylene production is in the range of 12–15 $GJ/t_{ethylene}$. In the case of UOP MTO, the lowest amount of 12 GJ/t ethylene is appropriate. In the case of ExxonMobil MTO, the energy consumption is about 25 GJ/t ethylene. The large difference between the SECs in the UOP MTO and the ExxonMobil MTO routes is the result of different product yields [14]. A brief overview of the other routes is explained at following sections.

Moreover, the advanced extraction technologies in recent years resulted in a boom of shale gas production in the United States and provides extra NGLs at low costs for the chemical manufacturing industry. As a result, manufacturing ethylene and propylene from shale gas-based feedstocks (e.g., ethane and propane), instead of from naphtha, is of growing interest [15].

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Production and consumption in Belgium – Ethylene is produced in Belgium by BASF and Total petrochemicals with capacities of $1080*10^3$ and $600*10^3$ t/y respectively [16].

Ethylene Production via Cracking of Ethane-Propane – Ethane is the most favored feedstock for steam cracker due to two key factors. First, ethane production costs are not sensitive to oil price levels, while naphtha-based producers need a lower oil price to remain competitive. Second, ethane-based production requires lower levels of feedstock input compared to naphtha. The ethane requirement of ethane cracker is 1.2 $t/t_{Ethylene}$ ton of ethylene, while around three tons of naphtha is needed to produce a ton of ethylene [17], [13]. In the other word, ethane-based production is more efficient and requires less feedstock for the same level of input [17]. The yield of ethylene at ethane based steam cracker is equal to 81% while the yields are 25% and 35% respectively for Gas oil and Naphtha based crackers [13].

The steam-cracking process for ethylene production from an ethane-propane mixture can be divided into three main parts: cracking and quenching; compression; drying, and separation [18]. Figure 1 depicts the process diagram of ethylene-production process via the cracking of an ethane-propane mixture [18].

Cracking and quenching - Initially, an ethane-propane mixture is fed to furnaces in which, under high-severity conditions, it is cracked, forming ethylene, propylene and other byproducts [18].

For the cracking of ethane, the steam dilution is required in amounts between 0.2 and 0.4 kg_{Steam}/kg_{Ethane}. After cracking, rapid reduction of gas temperature to 500 °C is necessary to avoid losses.

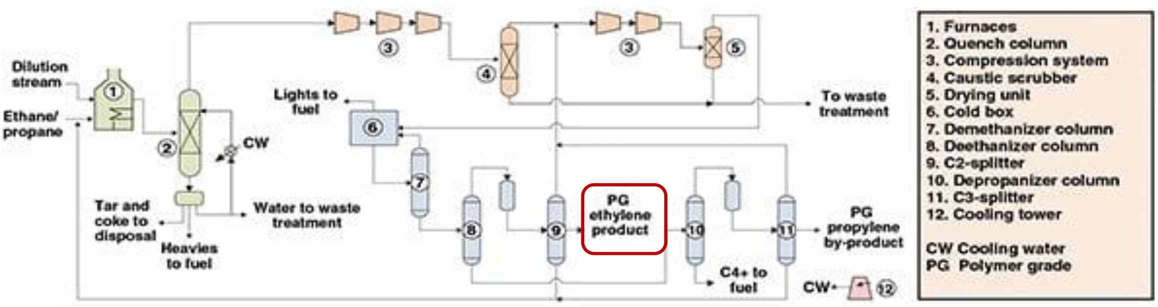

Figure 1. process diagram of ethylene-production process via the cracking of an ethane-propane mixture [18]

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Hence, the furnace outlet stream is subsequently fed to a water-based quench, to prevent further reactions and formation of undesirable byproducts [19]. Leaving the decanter downstream from the quench tower, heavies, condensed dilution steam, tar and coke are removed. Cracked gas from the quench is then directed to compression and separation [18].

Compression and drying - The compression of the cracked gas is performed across five stages. After the third stage of compression, carbon dioxide and sulfur are removed from the cracked gas by caustic soda and water washes in a caustic scrubber. The compressed cracked gas is cooled and subsequently dried by molecular sieves that remove most of the water [18].

Separation - The dried cracked gas is fed to a cold box for the removal of hydrogen and light hydrocarbons, while minimizing ethylene losses. At this point, condensates from the chilling train are fed to a series of separation columns. In the first column (demethanizer), methane is obtained from the top and further used in the cold box, while the bottom stream is fed to a second column (deethanizer). The top of the deethanizer, composed primarily of ethylene and ethane, is fed to an acetylene converter and then fractionated in the C_2-splitter. In this column, lights are removed from the overheads and recycled to the compression system, while polymer-grade (PG) ethylene is drawn from the column as a side stream. Ethane, from C_2-splitter bottoms, is recycled to the cracking furnaces [18].

Investment and production costs -

Estimated capital expenses (total fixed investment, working capital and initial expenses) to construct the plant for production of ethylene via cracking of ethane-propane are about 2.14 bn €$_{2015}$[3], while the operating expenses are estimated at about 324.32 €$_{2015}$ per ton of produced ethylene [18]. M. Yang et. al. has analyzed economic of two process designs for manufacturing ethylene and propylene from shale gas. They proposed co-cracking design and technology integrated design based on the raw shale gas composition [15]. Their calculations have determined the breakdown of production costs[4] for the

[3] 2.37 \$$_{2015}$ billion. The values are converted from \$ to € based on 1 €$_{2015}$ = 1.11 \$$_{2015}$ [54]; bn = billion
[4] Cost breakdown analysis is a method of cost analysis, which itemizes the cost of a certain product or service into its various components, the so-called cost drivers. The cost breakdown analysis is a popular cost reduction strategy and a viable opportunity for businesses [55].

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manufacturing of Ethylene equal to 287.21 $€_{2016}$ and 264.77 $€_{2016}$ [5] respectively for co-cracking and technology integrated design [15]. In the co-cracking design, the mixture of ethane and propane coming from the shale gas processing stage is co-cracked with the aid of steam. In the technology integrated design ethane–propane mixture are separated into ethane and propane in a natural gas liquids (NGL) fractionation unit. Ethane is fed into the ethane steam cracking unit, while propane is taken as the feedstock for the propane dehydrogenation unit [15].

Energy requirements – For the 197.3 t/h ethane–propane mixture as input and Ethylene production from Shale Gas equal to 125 t/h, the required energies are listed as utilities in table 1 [15].

Ethylene yield from MTO and MTP plants - The yield of ethylene at a common MTO plant is 0.4 $kg_{Ethylene}/kg_{Hydrocarbon}$ which is almost equal to the yield of propylene from MTO. However, by changing the process severity the propylene to ethylene ratio can reach values up to up to 2.1 [20]. Besides, Ethylene is one the byproducts at MTP plant with the small share of 0.08 $kg_{Ethyele}/kg_{Propylene}$ while the share of ethylene at naphtha based steam cracker is 2.44 times higher than propylene production [7].

Oxidative dehydrogenation of ethane to ethylene in an integrated CO_2

capture-utilization process - Al-Mamoori et. al. [1] have studied in-situ capture and utilization of CO_2 in ethylene production through oxidative dehydrogenation (ODH) of ethane over adsorbent-catalyst materials consisting of double salt K-Ca and Cr-impregnated H-ZSM-5 [1]. ODH approach seems to be a good option for the future ethylene production at relatively low temperature, pressure, and also by using cheaper feedstock such as ethane [21]**.** A mild oxidant such as CO_2 is a promising alternative to produce ethylene since it provides an opportunity to use underutilized ethane from shale gas (with a volume fraction of ~16 %). The ODH of ethane occurs at lower temperatures and subsequently at less energy than the steam cracking reaction [1].

[5] 1 $€_{2016}$ = 1.11 $\$_{2016}$ [54]

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Table 1. Required utilities for manufacturing Ethylene from Shale Gas via co-cracking design and technology integrated design [15].

	Co-cracking design	Technology-integrated design
Shale gas processing stage		
power (MW)*	97	139.7
LP steam (125 °C) (GJ/h)*	58.7	165.2
MP steam (175 °C) (GJ/h)*	13.3	17.1
HP steam (250 °C) (GJ/h)*	13.8	17.6
Olefins production stage		
power (MW)*	88.9	142.8
LP steam (125 °C) (GJ/h)*	414	1509
total fuel consumption (GJ/h)	2992	3977
external fuel demand (GJ/h)	1643	3397

* Power and steam are generated on-site

Oxidative dehydrogenation, unlike steam cracking and direct dehydrogenation, is a thermodynamically favorable, exothermic reaction forming water. Using an appropriate catalyst, ODH can operate at lower temperatures (300–550 °C) than steam crackers. The exothermic nature of the reaction together with the lower temperature requirement leads to more than 30% energy savings as compared to the steam cracking process. However, there is no commercial technology for ethane catalytic dehydrogenation and the key challenge in dehydrogenation reactions arise from their equilibrium-limited thermodynamics. In the case of oxygen-based oxidation, electricity is required for oxygen production, which demands for approximately 3–4 GJ/t_{oxygen} in primary energy terms [22]. Depending on the ODH process conditions and ratio of feedstocks the conversion and selectivity range of the reaction are 57-74% and 62-93% respectively [23]. The specific energy and specific feedstock requirements are, also, in range of 7-13 $kW/kg_{Ethylene}$ and 11-23 $kg_{Ethane}/kg_{Ethylene}$ respectively [23].

A.Talati et. al. [24] has investigated oxydative dehydrogenation of ethane to ethylene by carbon dioxide over $Cr/TiO_2–ZrO_2$ nano-catalyst. The catalyst loading for the reactor in their experimental setup was 500 mg. The reactant stream, consisting of 10 vol.% ethane, 50 vol.% carbon dioxide and 40 vol.% nitrogen, was introduced into the reactor. The reaction temperature ranged between 550 and 700 °C. The dehydrogenation and oxidative dehydrogenation due to the introduction of

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CO_2 and its decomposition to produce surface oxygen species will be the parallel reaction paths in the dehydrogenation of ethane by carbon dioxide. Ethane conversion reached the highest value (C_2H_6 conversion of 48% as well as 46% ethylene yield at 700 °C) when 75 wt.% TiO_2 and 25 wt.% ZrO_2 were used in support composition. Based on the results of other researchers, the possible reactions occurring are proposed as follows:

$$C_2H_6 \rightarrow C_2H_4 + H_2$$

$$2C_2H_6 + 2CrO_3 \rightarrow 2C_2H_4 + Cr_2O_3 + 3H_2O$$

$$Cr_2O_3 + 2CO_2 \rightarrow 2CO + 2CrO_3$$

$$H_2 + CO_2 \rightarrow CO + H_2O$$

$$C_2H_6 + 2CO_2 \rightarrow 4CO + 3H_2$$

$$C_2H_6 + H_2 \rightarrow 2CH_4$$

The oxidative dehydrogenation of ethane to ethylene in an integrated CO_2 capture-utilization process has, also, demonstrated a novel route for CO_2 utilization and manufacturing of value-added commodities [1].

Bio-ethylene - Ethylene can be produced from catalytically dehydrated ethanol, in which ethanol can be obtained from various biomass sources such as corn stover. Bio-ethylene can then be used in traditional polyethylene polymerization processes [25]. The production of ethylene from bioethanol dehydration is considered one of the most promising processes for industry [26]. However, the amount of biomass required per ton of ethylene produced and the output of the coproducts vary depending of the feedstock type and production route [27]. Moreover, the biomass-derived carbon emissions can be addressed in terms of its carbon neutrality. Basically, the fixed carbon captured by plants during growth should be included as negative emissions with equivalent amounts of emissions through the life cycle [28].

Catalytic dehydration of ethanol -

In 1797, Dutch chemists observed the formation of a gas through the passage of ethanol over alumina. The industrial production of ethylene by catalytic ethanol dehydration has been known since 1913 [29]. The ethylene production via fermentation technology is depicted in figure 2 [31]. Moreover, a simplified generic process diagram of an ethanol-based ethylene plant, through an isothermal or an adiabatic process, is presented in figure 3.

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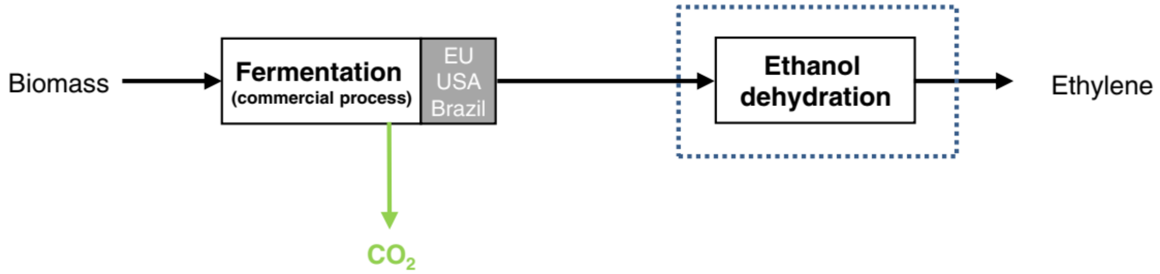

Figure 2. Outline of selected case study and system boundaries [31].

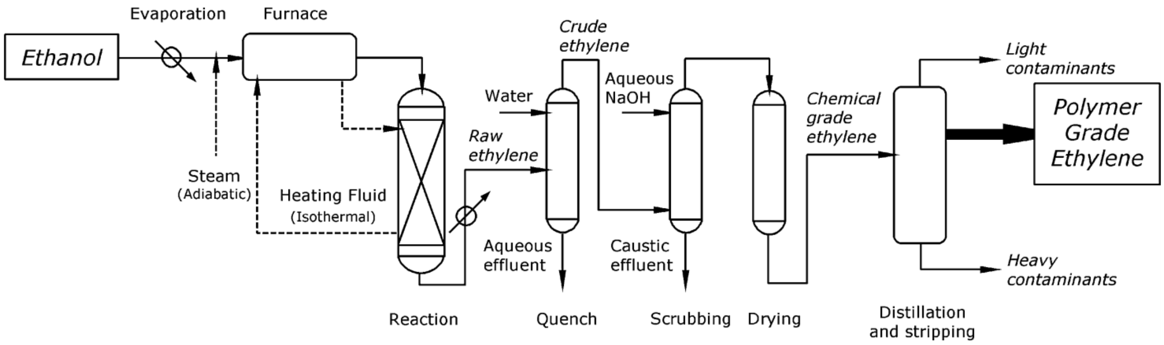

Figure 3. Representation of a generic process diagram of an ethanol-based ethylene plant [30].

Depending on the catalyst characteristics, its operational age and the dehydration process used, the ethanol conversion in one reactor is usually bigger than 95%, sometimes reaching as high as 99.5% and the reaction molar selectivity ranges from 95 to 99%. These parameters will have a direct influence on the raw ethylene purity and on the purification steps required to produce polymer grade ethylene [30].

Dehydration of ethanol can take place by two competitive paths. One is the intramolecular dehydration of ethanol to ethylene and the other is intermolecular dehydration of ethanol to diethyl ether. At lower temperature, diethyl ether is produced in significant quantities, while, at the higher temperature, ethylene is the dominant product [32].

In catalytic dehydration of ethanol, the reaction undergoes via suitable solid acid catalysts [33]. The most effectively used catalysts for catalytic dehydration of ethanol to ethylene are zeolites such as HZSM-5, beta zeolite, Si-Al-phosphate (SAPO) zeolite. Due to availability, HZSM-5 is the most used catalyst for catalytic ethanol dehydration [34]. In the catalytic dehydration of ethanol, ethylene is mostly formed by the parallel-consecutive

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pathway via intermediate formation of diethyl ether (DEE). Acetaldehyde and butylenes are the main by-products formed in small amounts. According to the overall heat effect of the occurring reactions, the process is endothermic, which is associated with the intense heat intake at a high input concentration of ethanol [35]. Implementing renewable ethanol as feedstock, catalytic dehydration of ethanol to ethylene is considered as a clean technology, which provides low CO_2 emission and energy consumption [33]. Bi et al. (2010) reported that the nanoscale HZSM-5 zeolite powder can provide a conversion rate of 98.6% and an ethylene selectivity of 99.2% at a reaction temperature of 240 °C. Moreover, the ability of H-ZSM-5 to catalyze the dehydration of ethanol to ethylene at low temperatures (200−300 °C) has made it commercially valuable and promising for further improvement in its efficiency [36].

Cost and energy of catalytic dehydration of ethanol - Several ethanol dehydration industrial plants are producing ethylene mainly located in Brazil, in which ethanol is produced via green routes. However, the ethylene production rate via ethanol dehydration is considerably less than its production via steam crackers [38]. A plant that produces 500,000 tons of ethylene per year would require 821,000 tons of ethanol, 22,000 tons of fuel, and a capital cost of 112.78 $M€_{2010}$[6] (compare with 526.32 $M€_{2010}$ for a cracking plant) [38].

Furthermore, based on an investigation by G. Cameron et. al. on the process design for the production of ethylene from ethanol, the total energy requirements of the plant is reported to be 112135.98 MJ/hr [37]. The production cost of ethylene would depend mainly on ethanol prices. The bioethanol cost accounts for about 60–75 % of the bioethylene production cost, depending on the region [38], [39]. As A. Mohsenzadeh et. al. reported, the production costs of bioethylene are very low in Brazil and India (from sugarcane, 1061.95 $€_{2017}$/t [7] bioethylene), while the costs are higher in United States (from corn, 1769.91 $€_{2017}$/t) and in European Union (from sugar beets, 2300.88 $€_{2017}$/t). The cost of Chinese bioethylene production from sweet sorghum is somewhere in between (about 1504.42 $€_{2017}$/t) [39].

In the ethylene production via fermentation technology for processing of 16.9–53.2 $t_{Ethanol}$/h, 4–13 MW electricity and 7–24

[6] 1 $€_{2010}$ = 1.33 $\$_{2010}$ [56]

[7] 1 $€_{2017}$ = 1.13 $\$_{2017}$ [54]

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MW natural gas[8] are required and the process yields 9.9–38.9 $t_{Ethylene}/h$ with energy efficiency of 81.8% [31]. The production costs for this case changes at different countries. The specific cost of this process for ethylene production is around 1.7 $€_{2013}/kg_{Ethylene}$ in Europe while it is around 1.2 $€_{2013}/kg_{Ethylene}$ and 1 $€_{2013}/kg_{Ethylene}$ in United States and Brazil respectively [31].

The International Renewable Energy Agency (IRENA) reported ethylene production costs at about 1550.39 $€_{2012}$[9] per ton from corn feedstock in the U.S. (930.23 $€_{2012}$ per ton from sugar cane feedstock, which is what the Braskem plant uses), while petrochemical ethylene only costs 465.12 $€_{2012}$ to 1007.75 $€_{2012}$ per ton [38]. Compared with the bioethylene production costs with the 1279.07 $€_{2012}$ per ton price of ethylene reported by PRNewswire, the bioethylene plant would not gain any revenue. However, using the algae technology instead of corn feedstock and more efficient catalysts like nano-HZSM-5 would significantly reduce production costs, and may make a bioethylene plant profitable. The bioethylene produced may also be sold with a green premium to increase profits [38].

Results of the other research by J. Becerra et. al. illustrated the Capex of 0.85 $M€_{2018}$[10] (61.02 $€_{2018}$/ton-year ethylene) and Opex of 3.98 $M€_{2018}$/year (286.44 $€_{2018}$/ton-year) for a plant that produces 13.9 Mton/year ethylene from bioethanol. These costs are comparable to those from the oil industry (Capex of 932.2 $€_{2018}$/ton-year and Opex of 274.58 $€_{2018}$/ton-year), showing the large opportunity for sustainable production of ethylene from bioethanol [26].

Oxidative coupling of methane -

Oxidative coupling of methane (OCM) is a direct route to obtain higher hydrocarbons from natural gas in a single step. OCM involves conversion of methane together with an oxidizing agent at high temperature (>750 °C) into the desired product C_2H_4 (or C_2H_6) and the main undesired by-products CO and CO_2. The main reactions involved in OCM are the following [40]:

$$2CH_4 + O_2 \longrightarrow C_2 + 2H_2O \qquad \Delta H^{\circ}_{298} = -141 KJ/mol\, CH_4$$
$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O \qquad \Delta H^{\circ}_{298} = -803 KJ/mol\, CH_4$$
$$C_2H_4 + 3O_2 \longrightarrow 2CO_2 + 2H_2O \qquad \Delta H^{\circ}_{298} = -1323 KJ/mol\, C_2H_4$$

[8] Ethanol production energy requirement is not included.

[9] 1 $€_{2012}$ = 1.29 $\$_{2012}$ [57]

[10] 1 $€_{2018}$ = 1.18 $\$_{2018}$ [58]

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The yield of higher hydrocarbons (C_2 and higher) is insufficient (≤ 30%) to make the OCM concept industrially feasible, which would require C_{2+} yields above 30–35%. One of most interesting concepts to carry out the OCM and to achieve an industrially feasible yield is the membrane reactor [40]. For example, a novel micro-reactor composed of a hollow fiber membrane which is made of $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-d}$ (LSCF), led to an excellent C_2 yield of 39% at an approximate methane conversion of 50%. However, thermal management of the exothermic reaction is a vital challenge ahead of the membrane reactor [41]. Following the C_{2+} production, separation unit and recycling of methane can improve the yield of the reaction [40].

CO_2 emission - Total CO_2 emission from natural gas-to-ethylene process is equal to 2.46 $t_{CO2}/t_{Ethylene}$. The GHG emission of naphtha based cracker is mainly from the process of naphtha and ethylene production, accounting for 26.8% and 57.1% of the total emission; the GHG emission of natural gas based ethylene production is mainly from the processes of natural gas-to-methanol and methanol-to-olefins, accounting for 57.5% and 21.5% of the total emission [12].

Carbon capture and storage (CCS) in Ethylene production – Due to the endothermic nature of the cracking reaction a high combustion duty has to be fired in the cracking furnaces. Steam crackers are producing a tail gas or methane fraction which is preferably burnt in the cracking furnaces to supply the heat necessary for the endothermic cracking reaction. Markus C. Weikl has studied carbon capture from Ethylene plant considering a set of five cracking furnaces with a total production of 80 t/h of ethylene [42]. Minimum required work and Cost for CO_2 emission from ethylene production via steam cracker is reported to be 9.4 – 12.8 (kJ/mol captured CO_2) and 34.6 - 46.6 (€$_{2014}$[11]/ton captured CO_2) at united states [45].

The amount of CO_2 emitted has a negative effect in plant economics under a cap-and-trade system[12] and is the main driver for

[11] 46 – 62 (\$$_{2014}$/ton captured CO_2) equal to 34.59 - 46.62 (€$_{2014}$/ton captured CO_2), 1 € $_{2014}$ = 1.33 \$ $_{2014}$ [60]

[12] Cap and trade is a common term for a government regulatory program designed to limit, or cap, the total level of emissions of certain chemicals, particularly carbon dioxide, as a result of industrial activity. Proponents of cap and trade argue that it is a palatable alternative to a carbon tax [59].

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establishment of a capture unit. The value of certificate costs is a variable in the cost model. The capture units have electrical demand on the one hand for oxygen generation and on the other hand for compression and purification. Compared to coal-fired power generation, specific demand for oxygen generation is approximately by a factor of 2 higher due to the lower carbon intensity of the fuel [42].

Among all CO_2 electro-reduction products, methane (CH_4) and ethylene (C_2H_4) are two typical and valuable hydrocarbon products which are formed in two different pathways: hydrogenation and dimerization reactions of the same CO intermediate. Theoretical studies show that the adsorption configurations of CO intermediate determine the reaction pathways towards CH_4/C_2H_4. However, it is challenging to experimentally control the CO adsorption configurations at the catalyst surface, and thus the hydrocarbon selectivity is still limited. Different catalysts are investigated for the aforementioned reaction such as copper Nano-catalysts with controllable surface structures which exhibit a high hydrocarbon selectivity toward either CH_4 (83%) or C_2H_4 (93%) under identical reduction conditions [43].

Ethylene manufacturing facilities are more clustered than any other major CO_2-emitting industry and responsible for a higher proportion than any other major CO_2 emitting industry. Assuming that increased facility size due to CCS installation does not exhibit increasing marginal costs any marginal costs the ethylene unit, this larger source is more attractive candidates for CO_2 capture than the smaller sources [44]. The CO_2 emission of ethylene production in the ethane and naphtha cracker are 1-1.2 $t_{CO2}/t_{Ethylene}$ and 1.8-2 $t_{CO2}/t_{Ethylene}$ respectively [13].

Manufacturing one tons of ethylene produces between 1 t_{CO2} (ethane feedstock) to 2 t_{CO2} (naphtha feedstock), and each ton of CO_2 costs 26.32 - 41.35 $€_{2013}/t_{CO2}$ to capture. Assuming that ethylene markets are competitive and therefore priced at their marginal cost, CO_2 capture would add 3.5 to 11% to the price of ethylene. Consequently, CO_2 capture from ethylene production results in a much lower increase in price than for fossil fueled electricity generation [44].

Ethylene production for indirect electrification of chemical industry

- Electrification is part of process

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intensification being explored by the chemical industry to improve energy efficiency and to reduce greenhouse-gas emission. Ethylene production, using electrochemical-facilitated non-oxidative ethane dehydrogenation, is an emerging, but promising, process to facilitate electrification of the ethylene industry and represents the most untapped opportunity in the chemical industry. Ethylene can be produced via low-temperature electrochemical route using solid-oxide membrane reactors/stacks (LoTempLene) and elucidate the opportunity of using it in the electrification trend. The single-pass ethylene yield for the LoTempLene reactor is predicted to be 48.5% by 2025 through optimization of the current state of technology, whereas 52.4% was applied for the steam-cracking reference process. Moreover, the operation cost of LoTempLene is 7% lower than that of steam cracking. Furthermore, steam-cracking process emits 1.47 ton of CO_2 per ton of ethylene, compared with 0.4 tons of CO_2 released from the LoTempLene process, resulting in a 72% reduce in CO_2 emission when grid electricity is used versus an 89% reduction when low-carbon electricity (e.g., nuclear, wind, or hydropower) is used [46].

Yearly estimated total direct CO_2 emissions related to Belgian Ethylene production volume – As it is explained at Propylene production fact sheet, the overview of the specific energy consumptions (SEC) and CO_2 emission for steam cracking which is the main route of ethylene production is included in table 2 for both feedstocks of ethane and naphtha [13]. Ethane based reactions requires less energy and leads to less CO_2 emission in comparison to the naphtha based ethylene production.

Table 2. Overview of energy use and CO_2 emissions of ethane and naphtha steam cracking

Feedstock	SEC		CO_2 emissions	
	($GJ/t_{ethylene}$)	(GJ/t_{HVC})*	($t_{CO2}/t_{ethylene}$)	(t_{CO2}/t_{HVC})
Ethane	17-21 15-25	16-19 12.5-21	1.0-1.2	1.0-1.2
Naphtha	26-31 25-40	14-17 14-22	1.8-2.0	1.6-1.8
Gasoil	40-50	18-23		

* HVC represents high value chemicals

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Table3. Summary Table: Key EO Data and Figures

Main production methods	**Feedstocks**	**Supply percentage in 2021[47]***	**Ethylene yield [48]**
Steam cracker	Ethane	40.1%	80%
	Naphtha	38.0%	30%
	LPG	13.3%	41%**
	Others (CTO[13]/MTO)	8.6%	-
ODH [14]	Ethane	- ****	46%[24] ***
MTO	Methanol	- ****	75%–80%[49] *****
Catalytic dehydration of ethanol[15]	Ethanol	- ****	9.9–38.9 ******
Ethylene production in Belgium			
Overall production rate (t/y)	$1680*10^3$		
Energy requirements based on the type of feedstock	**Electricity**		**Total energy consumption**
Steam cracker (Naphtha-based)	44 ($kWh/t_{Ethylene}$)		120 ($GJ/t_{Ethylene}$) [13]
ODH	7-13 ($kW/kg_{Ethylene}$) [23]		5.09 ($GJTh/t_{HVP}$) [50] (Exothermic process) [51]
MTO	-		12–15 ($GJ/t_{Ethylene}$)[14]
Catalytic dehydration of ethanol	4–13 MW [16]		7–24 MW (natural gas) [17]
Costs			
Steam cracker	748 $€_{2017}/t_{Ethylene}$ [52]		
ODH	372.57 ($€_{2017}$ [18]/ $t_{Ethylene}$) [51]		
MTO	588.99 ($€_{2018}$ [19]/ $t_{Ethylene}$) [53]		
Catalytic dehydration of ethanol	2300.88[20] ($€_{2017}/t_{Bio\text{-}Ethylene}$) [39]		

* Estimated values at 2016 for 2021. Data for 2016 is, also, available in the referenced document.
** Average value
*** The yield can change depending on the catalyst
**** Less than 8.6% and in included at others at supply percentage box.
***** With SAPO-34 catalyst [49].
****** Via fermentation process. This value depends on the feedstock and process

[13] Including (CTO[13]/MTO); CTO = Coal to Olefins
[14] Oxidative dehydrogenation of ethane
[15] This route is mainly discussed for green ethylene production
[16] For processing of 16.9–53.2 $t_{Ethanol}/h$
[17] For processing of 16.9–53.2 $t_{Ethanol}/h$
[18] 1 $€_{2017}$ = 1.13 $\$_{2017}$ [54]
[19] Converted from Chinese Yuan to Euro, 1 $€_{2018}$ = 7.81 Chinese Yuan [61]
[20] In Europe. Price depends on the region of production

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