

S2Biom Project Grant Agreement n°608622

Deliverable 7.2c
**Market analysis of biomethane, BTX, methanol,
hydrogen, ethylene, and mixed alcohols**

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About S2Biom project

The S2Biom project - Delivery of sustainable supply of non-food biomass to support a “resource-efficient” Bioeconomy in Europe - supports the sustainable delivery of non-food biomass feedstock at local, regional and pan European level through developing strategies, and roadmaps that will be informed by a “computerized and easy to use” toolset (and respective databases) with updated harmonized datasets at local, regional, national and pan European level for EU-28, Western Balkans, Moldova, Turkey and Ukraine. Further information about the project and the partners involved are available under www.s2biom.eu.

Project coordinator



Scientific coordinator



Project partners



About this document

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Executive summary

The main aim of the S2Biom project is to support the sustainable delivery of non-food biomass feedstock at local, regional and pan European level through developing strategies and roadmaps that will be informed by a “computerized and easy to use” toolset (and respective databases) with updated harmonized datasets at local, regional, national and pan European level for EU28, Western Balkans, Moldova, Turkey and Ukraine. The research work foreseen will cover the whole biomass delivery chain from primary biomass to end-use of non-food products and from logistics, pre-treatment to conversion technologies.

As a part of this the S2Biom project explores perspectives for producing energy and materials from lignocellulosic biomass. The crucial general question to be addressed in WP7 is under which conditions there will be sufficient biomass to meet the EU renewable energy objectives (and the role biomass has to play in that) and provide a good feedstock basis for novel biobased chemicals and materials. An element in WP7 is an analysis of the markets for biobased industries. This task builds further on techno-economic data collected in WP2 and provides additional relevant information for the integrated assessment of tasks 7.3-5.

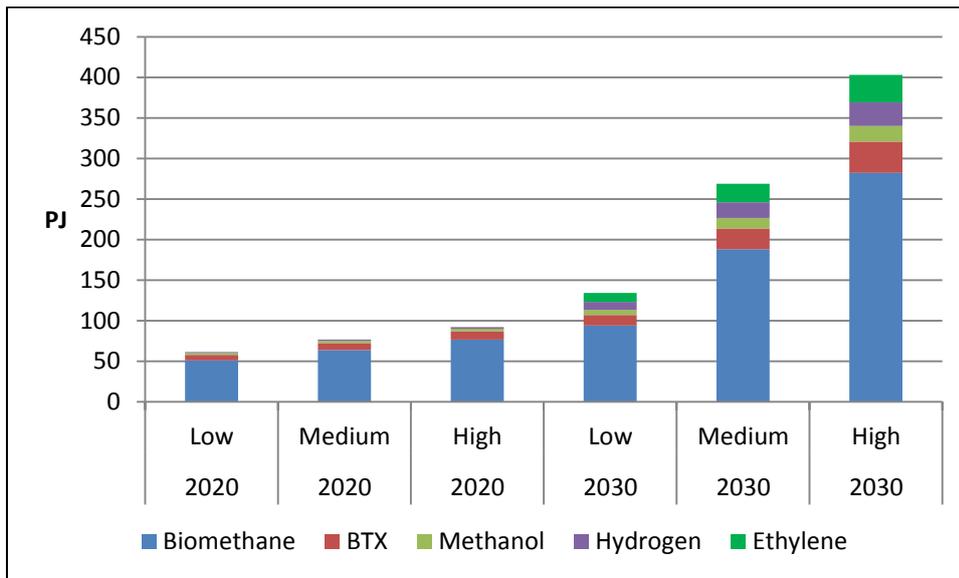
For the market analysis 10 PMCs (product-market combinations) were identified as possible significant consumers of biomass resources in the Pan-European area. The focus was to quantify the demand for biomass feedstock for these PMCs in 2020 and 2030. The considered PMCs are¹:

1. Heat
2. Electricity
3. (Advanced) biofuels
4. C6 chemistry
5. C5 chemistry
6. Biomethane
7. Aromatics (BTX)
8. Methanol
9. Hydrogen
10. Ethylene

The PMCs discussed in this market review are part of the deliverable 7.2 and include biomethane, aromatics (BTX), methanol, hydrogen, ethylene, and mixed alcohols.

¹ Originally, three more PMCs were identified: lignin, bioethanol and mixed alcohols. Current bioplastic routes only use the cellulose and hemicellulose parts of the lignocellulosic feedstock. Lignin is a more complex resource for which less biochemical pathways are available today. It is expected, that lignin up to 2030 would mainly be used as a source of bioenergy. Bioethanol has been considered as a biofuel within the third PMC, and as a biochemical in the dehydration reaction for the production of bio-ethylene (PMC 10). The process of mixed alcohol production is still at the early stage of development. No data is found for the conversion efficiency of this process. The process is mostly developed in the USA (NREL), where the major focus lies on renewable alternatives for fossil-based gasoline. An alternative to this process in Europe is ethanol production via biochemical conversion of lignocellulosic biomass.

Based on the assumptions made, and the analyses performed for these PMCs, the total demand for lignocellulosic biomass feedstock for these PMCs² in 2020 and 2030 has been quantified, as presented in figure below. The demand for the Medium Scenario (MS) would be 77 PJ in 2020 and 269 PJ in 2030. Also the expected biomass demands based on Low and High Scenarios for 2020 and 2030 are presented in the figure³.



² Excluding the mixed alcohols PMC, due to a lack of required information.

³ Low Scenarios: 2020 (80% MS), 2030 (50% MS); high Scenarios: 2020 (120% MS), 2030 (150% MS)

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1. Biomethane

1.1. Applications

Methane or natural gas is a fuel currently used in the heat and/or power application(s), and as an alternative fuel to gasoline in the transport sector. Besides, it is used in the (petro)chemical industry as feedstock for the synthesis of different (petro)chemical products. Biomethane can replace fossil-based methane or natural gas in all the above-mentioned applications/markets (see Table 1).

Table 1: Biomethane product market combination

Interm. product	Interm. market	Final product	Final Market
		Biomethane	Grid
		Biomethane	Transport fuel

1.2. Biobased production routes

Biomethane is produced from anaerobic digestion of biodegradable municipal solid waste (MSW), sewage sludge, manure, wet wastes (farm and food wastes), and macro-algae, followed by a biogas upgrading step. Biomethane can also be produced via gasification of biomass to a product gas, followed by a secondary process consisting of water-gas shift and methanation reactions and methane separation [1]. Biomethane produced from gasification of biomass is also called bio-SNG (SNG: substitute natural gas).

The Netherlands have a relatively long history concerning the production and injection of biomethane into the natural gas grid. The first projects, upgrading landfill gas to natural gas quality are dated from the mid 80's of the last century. Since 2008 the new Dutch renewable energy subsidy scheme introduced an incentive for biomethane production. In 2012, 0.718 PJ (about 22 million m³) of green gas was produced in the Netherlands [2]. The Netherlands is also actively involved in the development of biomethane (bio-SNG) production through the gasification of wood.

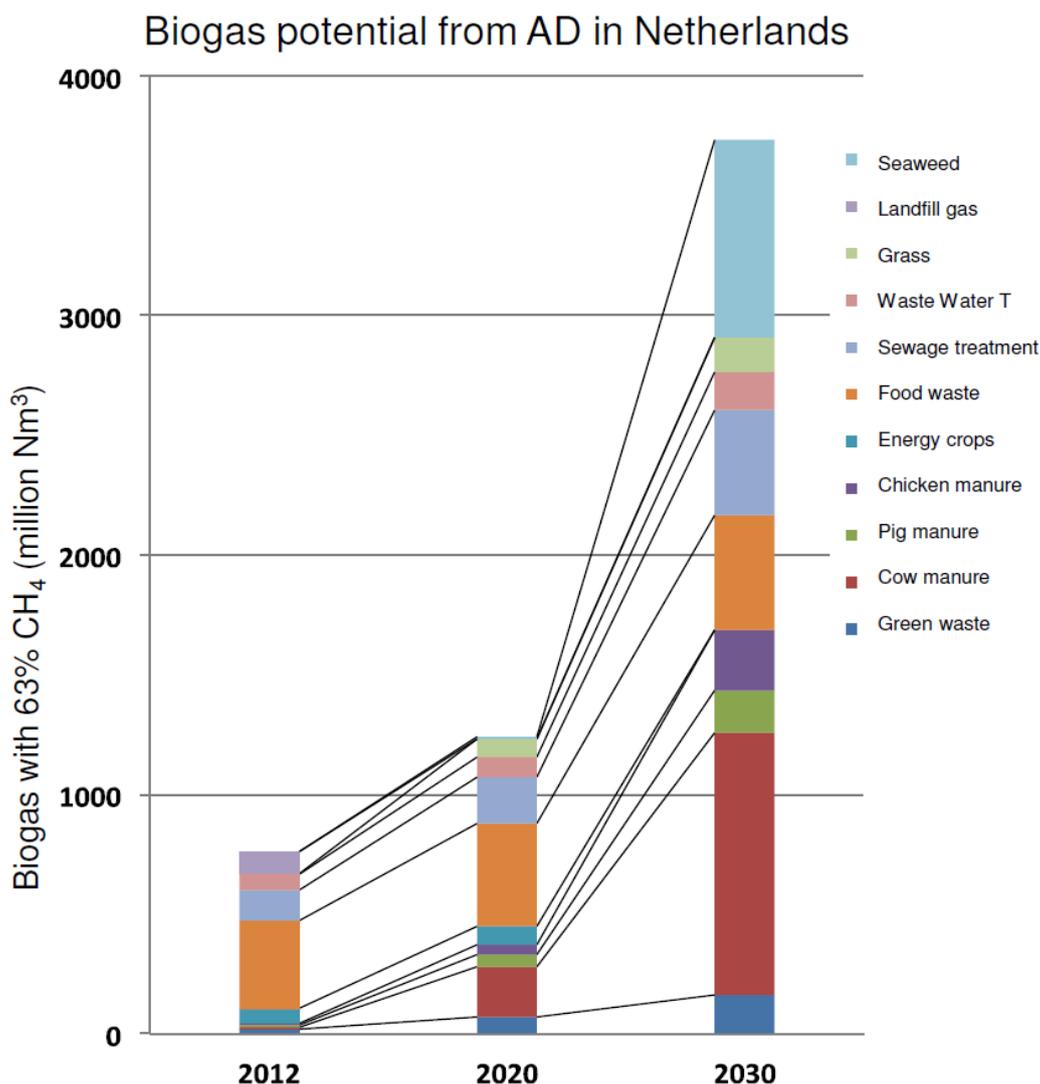
The annual Dutch primary energy consumption is 3300 PJ, with a natural gas contribution of more than 1500 PJ (46%). In 2011 the Dutch Biomethane Foundation presented the following projection for biomethane production in the Netherlands [3]:

- 2014: 300 millions m³ (2600 GWh) based on digestion
- 2020 - 2025: 1.5 – 2.0 billions m³ (13 – 17 TWh) based on both digestion and gasification (3 – 4% of the current Dutch natural gas consumption)
- 2030: 3.0 billions m³ (26 TWh) based on both digestion and gasification (6% of the current Dutch natural gas consumption)

- 2050: 30 billions m^3 (260 TWh). This is equal to 62% of the current Dutch natural gas consumption, or 28% of the current Dutch primary energy consumption.

Figure 1 gives an estimation of the maximum potential of the different disposal routes for biogas from anaerobic digestion in 2020 and 2030 [4]. Based on the wet biomass potential in the Netherlands, about 1.2 billion m^3 of biogas (with 63% methane content) can be produced via digestion in 2020. This is equal to 0.76 billion m^3 methane. In 2030 about 3.7 billion m^3 of biogas can be produced, equal to 2.34 billion m^3 methane. Herewith anaerobic digestion can potentially cover about 75% of the Dutch biomethane ambition in 2030 (3 billion m^3 methane). In practice, however, the produced biogas would be used for different applications, such as bio-heat and bio-CHP, including a fraction upgraded to biomethane.

Figure 1: Estimation of the maximum potential for biogas (with 63% methane in million nm^3) from anaerobic digestion in 2020 and 2030 in the Netherlands) [4]



1.3. Types and amount of feedstock used

1.3.1. Anaerobic digestion

Table 2 presents the potential contribution of anaerobic digestion in 2020 and 2030 to the Dutch biomethane ambition. It is assumed, that only 50% of the produced biogas would be available for upgrading to biomethane.

Table 2: Contribution of anaerobic digestion to Dutch biomethane ambition

	Unit	Value
Dutch ambition biomethane 2020	Billion m3	1
Dutch ambition biomethane 2030	Billion m3	3
Contribution digestion 2020	Billion m3	0.38
	PJ ⁴	13.57
Contribution digestion 2030	Billion m3	1.17
	PJ	41.84

1.3.2. Biomass gasification

The gasification process is based on the indirect gasification of solid biomass. The gasification section consists of two fluidized-bed reactors: gasifier and combustor. Biomass is fed into gasification chamber, and converted to nitrogen-free fuel gas (product gas) and char using steam. The char is burnt in air in the combustion chamber, heating bed particles, bed material is fed back into the gasification chamber providing heat for gasification reactions. Product gas is cooled and filtered and tars are removed in an oil scrubber. Partially cleaned gas is led into final gas cleaning and conditioning unit after which it is pressurised and led into methanation. Methanation takes place either within a fluidized bed reactor that has been developed specifically for the biomass-to-SNG process by PSI and CTU from Switzerland, or in existing fixed bed methanation technology. Depending on the concept, CO₂ removal can take place prior, or downstream methanation step using, a.o., amine scrubbing. Further conditioning to bio-SNG includes at least a gas drying step [5].

Table 3 presents the technical specification of biomass gasification process for biomethane production. As feedstock wood pellets as well as pruning & thinning wood have been considered.

Table 4 presents the potential contribution of biomass gasification in 2020 and 2030 to the Dutch biomethane ambition. It is assumed, that bio-SNG produced from gasification process would cover the ambition, together with biomethane from anaerobic digestion, up to 1 billion m³ in 2020, respectively 3 billion m³ in 2030.

⁴ LHV methane = 35.9 MJ/m³

Table 3: Technical specification of biomass gasification for biomethane production

	Unit	Value
Biomass input	MW _{th}	150
Biomethane Production efficiency	%LHV _{input}	70
LHV (wood pellet)	GJ/t _{ar}	17 [6]
LHV (pruning & thinning wood)	GJ/t _{ar}	9 [6]

Table 4: Contribution of biomass gasification to Dutch biomethane ambition

	Unit	Value
Dutch ambition biomethane 2020	Billion m3	1
Dutch ambition biomethane 2030	Billion m3	3
Contribution gasification 2020	Billion m3	0.62
	PJ ⁵	22.33
Contribution gasification 2030	Billion m3	1.83
	PJ	65.86

1.3.3. From Dutch to a European level

The Dutch biomethane ambition might be considered as the upper limit for biomethane production in the Netherlands. Therefore, we assume that 50% of the Dutch ambition would be realized in 2020 and 2030. On the other hand, at a European level a number of countries are currently active in biomethane production (NL, SE, DE, AT, CH, UK, FR). In France, for instance, there is a feed in tariff of 65-95 €/MWh for green gas. According to a scenario for 2050, 30 TWh (108 PJ) of green gas would be realized via gasification, 64 TWh (230 PJ) via anaerobic digestion, and 14 TWh (50 PJ) via power-to-gas route. GdF has the objective to realize 5% green gas in 2020 and 20% in 2030 [7].

As a first estimation, it is assumed that the projection for biomethane production via gasification at the EU level would be four times as the assumed biomethane production via gasification in the Netherlands.

Table 5 presents the current and expected production of biomethane via gasification in Europe. Table 6 presents the total solid biomass demand for the biomethane PMC in Europe.

Table 5: Current and expected production of biomethane via gasification in Europe

	Unit	Value
Current production	PJ	0
Expectation 2020	PJ	44.6
Expectation 2030	PJ	131.7
Low Scenario 2020	%MS	80
High Scenario 2020	%MS	120
Low Scenario 2030	%MS	50
High Scenario 2030	%MS	150

⁵ LHV methane = 35.9 MJ/m³

Table 6: Total solid biomass demand for biomethane PMC

	Current	2020		2030	
	kt _{air} /a	kt _{air} /a	PJ	kt _{air} /a	PJ
Wood pellets					
Low Scenario	0	3002	51.0	5534	94.1
Medium Scenario	0	3753	63.8	11069	188.2
High Scenario	0	4503	76.6	16603	282.3
Pruning and thinning wood					
Low Scenario	0	5671	51.0	10454	94.1
Medium Scenario	0	7089	63.8	20907	188.2
High Scenario	0	8507	76.6	31361	282.3

2. Aromatics (BTX)

2.1. Applications

BTX is a term used in the petrochemical industry for aromatics benzene, toluene and xylene. BTX is an intermediate product being used as feedstock in the petrochemical industry to produce final products for the chemical industry and transport sector (see Table 7). Benzene is a raw material for, among others, polystyrene plastics. Toluene is used as a solvent and added to gasolines with high octane numbers. Ortho- and para-xylene are raw materials for the production of plasticizers, polyester fibers, films and resins. A well-known product that is produced from para-xylene is polyethylene terephthalate (PET) for soft drink bottles [8].

Table 7: BTX product market combination

Interm. product	Interm. market	Final product	Final Market
BTX	Petrochemical industry	Polystyrene	Chemical industry
BTX	Petrochemical industry	PET	Chemical industry
BTX	Petrochemical industry	Fuel additives (Toluene)	Transport sector

2.2. Market

Aromatics (BTX) are very important raw materials for chemical and polymer industries. The global market for aromatics is growing by 5-10% per year [8]. Current (2010) US demand for BTX is around 21 million tonnes per year [9].

In 2013, the West European benzene consumption was 7,636 kt, the benzene production was about 6,800 kt, while the benzene production capacity was about 10,000 kt [10].

Figure 2 presents the West European benzene capacity, production and consumption in the period 1994 to 2013. Figure 3 gives the consumption of benzene in Western Europe by derivative in 2013. Finally, Figure 4 presents the historical West European benzene consumption by derivative in the period 1994 to 2013 [10].

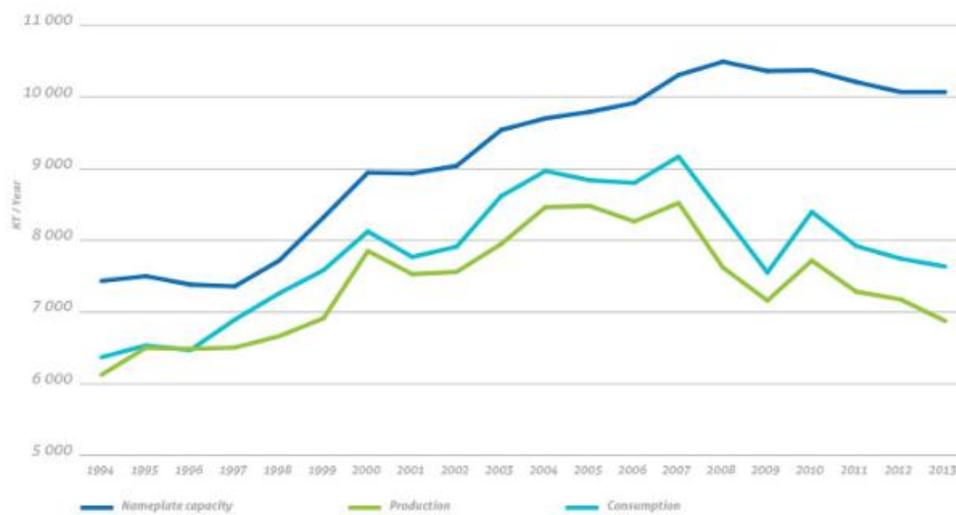
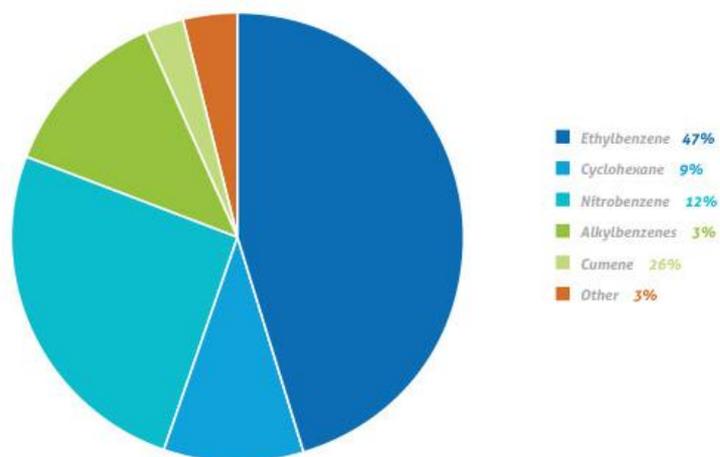
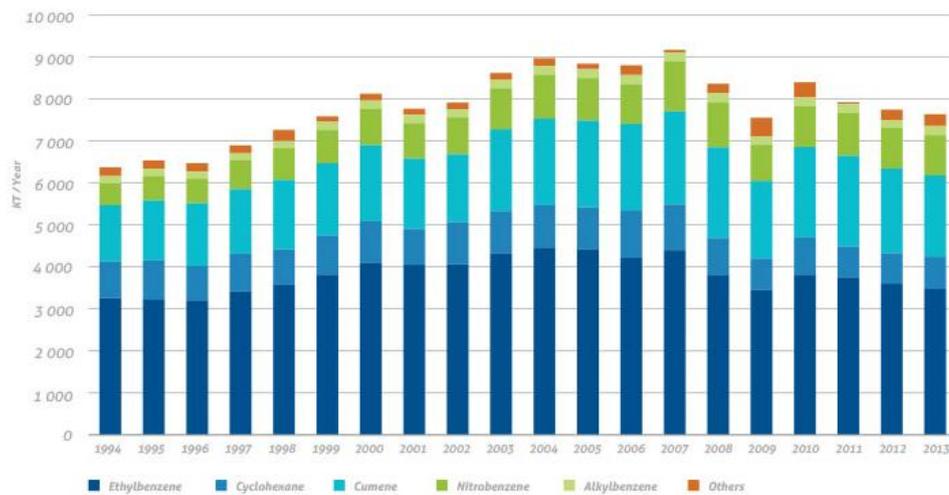
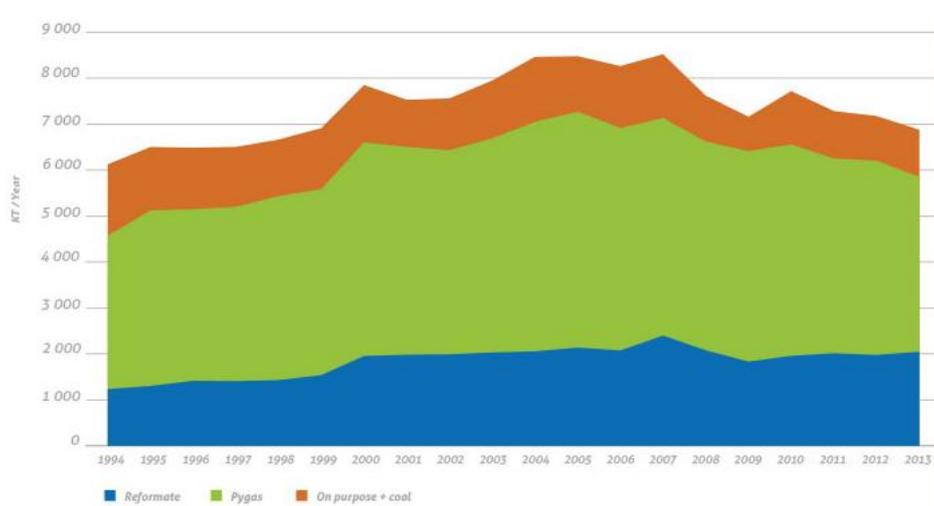
Figure 2: West European benzene capacity, production and consumption 1994-2013 [10]

Figure 3: West European benzene consumption by derivative 2013 [10]


Figure 4: Historical West European benzene consumption by derivative 1994-2013 [10]


2.3. Reference (fossil) production routes

Figure 5 presents the historical West European benzene production by source in the period 1994 to 2013 [10]. Benzene is extracted from two primary sources: from pyrolysis gasoline (pygas) which is a co-product of ethylene manufacture, or from reformat, a stream resulting from the catalytic reforming process used to produce high octane gasoline. Benzene can also be derived from toluene via two on-purpose routes: hydrodealkylation and disproportionation. Finally, it can be derived from coal.

Based on Figure 5, in 2013, the contribution of these routes to benzene production was respectively 55.3% (pygas), 29.7% (reformat), and 15% (on-purpose + coal).

Figure 5: Historical West European benzene production by source 1994-2013 [10]


2.4. Biobased production routes

Since a few years, the research on production of aromatics based on organic materials has increased strongly. Roughly three strategies are followed for the production of bio-aromatics [8]:

1. Reforming of lignocellulosic biomass to fuels, with BTX as a byproduct;
2. Fermentation of carbohydrate-rich streams into isobutanol, followed by conversion to BTX;
3. Production of BTX from lignin.

All routes have significant drawbacks. In case of the first route, there should be a relatively large market for fuels, as BTX is only released as a byproduct. The second route has an unfavourable theoretical yield and produces a lot of CO₂ as a by-product. The yield of the third route is also low, however, the lignin that cannot be transformed to BTX can be converted to biomethane. Moreover, route 3 has in any case the advantage that the raw material (lignin) already has a ring structure, that it is available in large quantities, and that it currently has a low economic value.

2.5. Type and amount of feedstock used

As a biobased route for the production of BTX, we focus on the gasification of solid biomass. This process can be either optimized for maximum bio-SNG (substitute natural gas) production, such that bio-SNG efficiencies up to 70% ($\%LHV_{\text{biomass input}}$) could be achieved, or it can be optimized for maximum BTX production, with BTX efficiencies up to 15% ($\%LHV_{\text{biomass input}}$) and bio-SNG efficiencies up to 55% ($\%LHV_{\text{biomass input}}$). In Chapter 1 the assumptions regarding the expected biomethane production in 2020 and 2030 are based on the maximum bio-SNG production. In this chapter it is assumed, that the expected production levels in 2020 and 2030 for 50% of the facilities are based on the maximum BTX production. For these facilities, in order to still produce the same amount of bio-SNG as in Chapter 1, the expected required biomass input in 2020 and 2030 are multiplied by 70%/55%.

Table 8 presents the technical specification of biomass gasification process for optimized BTX production. As feedstock wood pellets as well as pruning & thinning wood have been considered. Table 9 presents the current and expected production of BTX via gasification of solid biomass. The expected values for 2020 and 2030 (150 kt, resp. 450 kt) are 2% resp. 6% of the West European benzene consumption in 2013 (7636 kt). Finally, Table 10 summarizes the total amount of the selected biomass types expected for the bio-BTX PMC.

Table 8: Technical specification of biomass gasification process for optimized BTX production

	Unit	Value
Biomass input	MW _{th}	150
SNG	%LHV _{input}	55
BTX	%LHV _{input}	15 [11]
LHV (BTX)	MJ/KG	40 [11]
LHV (wood pellet)	GJ/t _{ar}	17 [6]
LHV (pruning & thinning wood)	GJ/t _{ar}	9 [6]

Table 9: Current and expected production of BTX via gasification of solid biomass

	Unit	Value
Current production	kt	0
Expectation 2020	kt	150
Expectation 2030	kt	450
Low Scenario 2020	%MS	80
High Scenario 2020	%MS	120
Low Scenario 2030	%MS	50
High Scenario 2030	%MS	150

Table 10: Total biomass demand for bio-BTX PMC

	Current	2020		2030	
	kt _{ar} /a	kt _{ar} /a	PJ	kt _{ar} /a	PJ
Wood pellets					
Low Scenario	0	3412	58.0	6289	106.9
Medium Scenario	0	4265	72.5	12578	213.8
High Scenario	0	5118	87.0	18867	320.7
Pruning and thinning wood					
Low Scenario	0	6444	58.0	11879	106.9
Medium Scenario	0	8055	72.5	23758	213.8
High Scenario	0	9667	87.0	35638	320.7

3. Methanol

3.1. Applications

Methanol is a basic, one-carbon molecule that enables an almost countless number of chemical processes. It is an intermediate product being used as feedstock in the chemical industry to produce final products such as MTBE, DME, FAME, formaldehyde, and acetic acid for the transport sector and chemical industry (see Table 11).

Table 11: Methanol product market combination

Interm. product	Interm. market	Final product	Final Market
Methanol	Chemical industry	Methanol	Transport sector
Methanol	Chemical industry	MTBE	Transport sector
Methanol	Chemical industry	DME	Transport sector
Methanol	Chemical industry	FAME	Transport sector
Methanol	Chemical industry	Formaldehyde	Chemical industry
Methanol	Chemical industry	Acetic acid	Chemical industry

Made mostly from natural gas, it is at the trailhead of hundreds of value-chain pathways that lead through the realms of petrochemicals, alkalis, thiols, and life sciences chemicals, eventually leading to critical applications that modern society demands. Accordingly, methanol is a strategic chemical for a vast array of petrochemical industry participants [12].

Major uses for methanol are depicted in Table 12 [12].

Table 12: Major methanol derivative uses [12]

<u>Primary Derivative</u>	<u>Secondary Derivative</u>	<u>Tertiary Derivative</u>	<u>Quaternary Derivative</u>
Acetic Acid	Vinyl Acetate Acetic Anhydride Terephthalic Acid	Polyvinyl Acetate Cellulose Acetate (filter tow) Polyesters (polyethylene terephthalate)	Polyvinyl Alcohol EVA
Formaldehyde	Phenol Formaldehyde Resins Urea Formaldehyde Resins Melamine Resins Polyoxymethylene (POM or Polyacetal) Polyols Butanediol MDI Isoprene Paraformaldehyde Hexamine	Polyesters (polybutyl terephthalate) Rubber (polyisoprene)	
Methyl tert-butyl ether (MTBE)			
Methyl Methacrylate	Polymethylmethacrylate (PMMA) Methacrylate/Acrylate Co Polymers		
Methyl Chloride (Chloromethane)	Methylene Chloride (CH ₂ Cl ₂)	Chloroform (CHCl ₃)	Carbon Tetrachloride
Methylamines Monomethylamine	Caffeine (stimulant, diuretic) Sevin/carbaryl (insecticide) Various other insecticides Various other herbicides Various other pesticides Water gel explosives Photographic developers Analgesics (Demerol) Antispasmodics		
Dimethylamine	Fungicides Dimethyl Formamide (solvent) Rubber accelerators, processing agents Propellants antihistamatic (Benadryl) Catalysts (Urethane) Surfactants Water Treatment Detergents Germicides Herbicides Epoxy Resin Accelerators		
Trimethylamine	Acid Scavenger (Nylon, Benzyl Esters) Choline Chloride Ion Exchange Resins (with crosslinked polystyrene) Gelling Inhibitor (Polyester)		
Others			
Dimethyl terephthalate (DMT)		Polyesters	
Reducing agent	Purified Terephthalic Acid (PTA)		
Methyl Mercaptan (methanethiol)	Chlorine Dioxide DL-methionine (amino acid)		
Developmental Uses			
Direct Uses (gasoline blending)			
Fuel Cells			
Methanol-to-Olefins			

There is also significant commercialisation effort underway in two developmental uses for methanol: fuel cells and methanol-to-olefins (MTO or GTO – gas to olefins). Fuel cells can utilize the hydrogen molecules of methanol (as well as other fuels) to create electricity (and water). MTO/GTO utilizes methanol as an intermediary step in the production of olefins and their derivatives (ethylene, propylene, polyethylene, polypropylene). All of these “alternative fuel” uses for methanol have significant hurdles in their commercialisation, but high potential demand [12].

3.2. Market

Table 13 presents the global supply and demand of methanol over the period 2008 to 2013 [12].

Table 13: Methanol supply and demand balance (*1000 tonnes) [12]

	2008	2009	2010	2011	2012	2013E	CAGR 08-13E
Supply							
Nameplate Capacity	59,014	67,454	76,478	86,777	95,469	101,063	11.4
Adjustments	-	-	-	-	-	(1,800)	
Total Capacity	59,014	67,454	76,478	86,777	95,469	99,263	11.0
Macro Operating Rate	68.2%	62.3%	63.9%	63.1%	63.5%	65.1%	
Production	40,260	42,051	48,892	54,749	60,589	64,575	9.9
Imports	20,231	22,503	23,812	24,344	23,860	25,034	4.4
Total Supply	40,260	42,051	48,892	54,749	60,589	64,575	9.9
Demand							
Formaldehyde	15,160	14,163	16,284	17,569	18,410	19,316	5.0
Acetic Acid	4,278	4,244	4,986	5,189	5,307	5,704	5.9
Methyl tert-Butyl Ether (MTBE)	6,985	6,749	7,265	7,673	8,169	8,521	4.1
Methyl Methacrylate	1,328	1,261	1,410	1,462	1,507	1,579	3.5
Dimethyl terephthalate (DMT)	487	467	453	457	458	468	-0.8
Methanethiol (Methyl Mercaptan)	432	425	420	444	461	478	2.0
Methylamines	1,167	1,132	1,280	1,360	1,401	1,441	4.3
Methyl Chloride (Chloromethane)	1,713	1,691	1,782	1,857	1,916	1,987	3.0
Alternative Fuels							
Gasoline Blending & Combustion	3,091	4,903	6,158	7,143	8,311	9,224	24.4
Biodiesel	909	832	903	1,210	1,314	1,218	6.0
DME	1,824	3,338	3,977	4,297	4,557	4,734	21.0
Fuel Cells	10	5	6	6	7	7	-6.4
Methanol-to-Olefins	7	7	702	2,479	4,908	5,886	289.5
Others	3,038	2,824	3,307	3,584	3,872	4,014	5.7
Total	40,428	42,042	48,932	54,731	60,597	64,575	9.8
Exports	20,231	22,503	23,812	24,344	23,860	25,034	4.4
Total Country Demand	40,428	42,042	48,932	54,731	60,597	64,575	9.8
Net	(168)	9	(39)	19	(8)	-	

Figure 6 and Figure 7 present the 2013E⁶ methanol demand and supply by major region [12]. It can be seen that Europe is for a great extent dependent on the import of methanol, as it has 12% of the global demand for methanol, while it contributes only for 4% to the global supply of methanol.

Figure 6: 2013E methanol demand by major region [12]

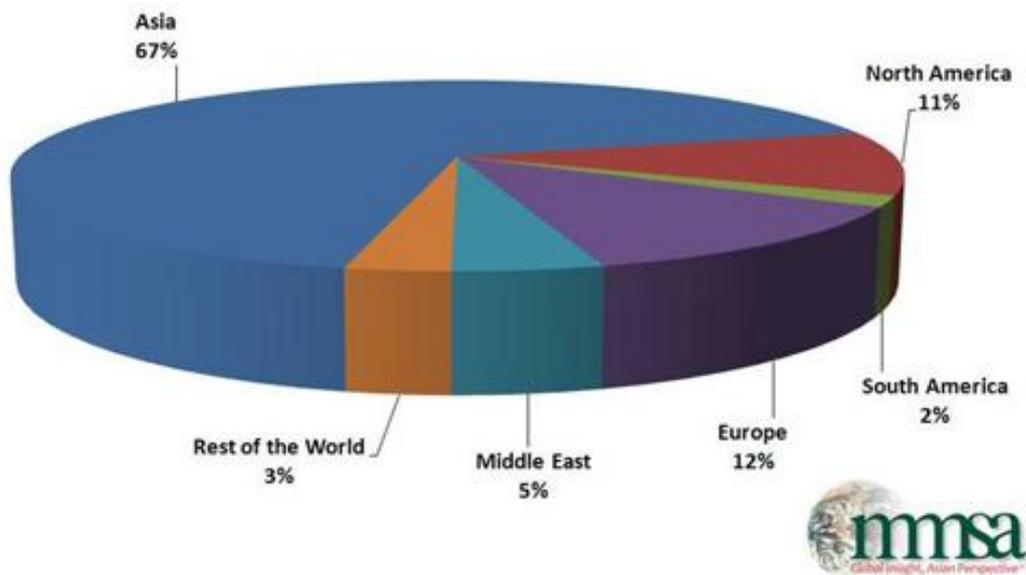
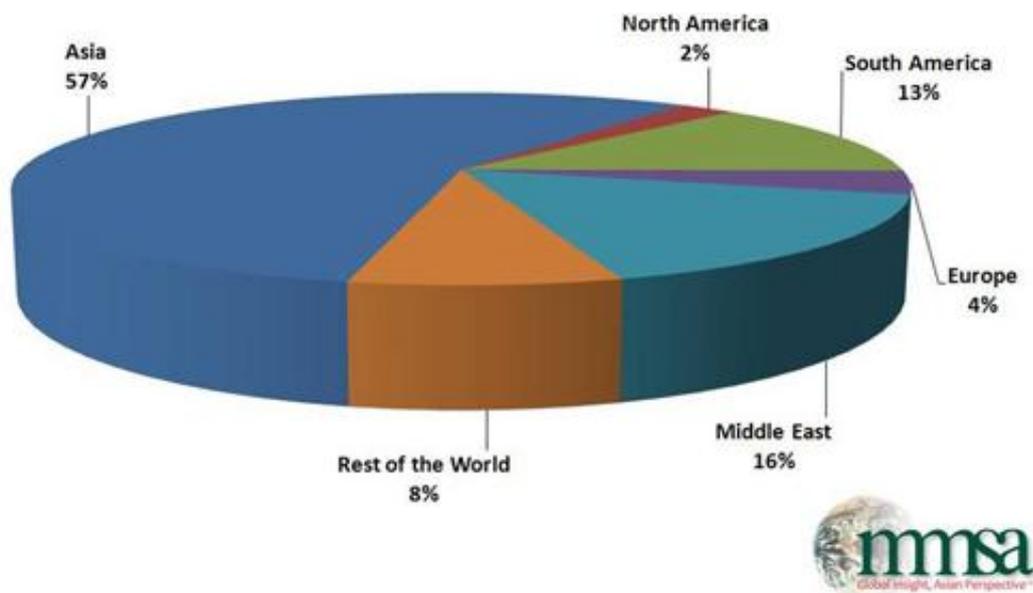


Figure 7: 2013E methanol supply by major region [12]



⁶ Estimate

3.3. Reference (fossil) production routes

Methanol is made from synthesis gas (syngas), which itself is the product of hydrocarbon-rich material that has been heated in the presence of metal catalysts. Almost exclusively, that hydrocarbon is natural gas (methane). However in China, a large amount of production capacity uses coal as the source of hydrocarbons.

3.3.1. Natural Gas Based Methanol Production

Methanol production from syngas takes place in three major steps:

1. reforming, the catalyzed production of syngas from saturated, de-sulphurized natural gas (reformation)
2. methanol synthesis with a Cu/Zn/Alumina catalyst
3. and finally, crude methanol (water containing) purification via distillation.

3.3.2. Coal Based Methanol Production

Coal is the only other significant commercial feedstock for methanol production, and its use is concentrated in coal-rich China. The production of syngas from coal has been a commercial reality since the 1920's. The process also follows the three main steps of the natural gas process.

3.4. Biobased production routes

Methanol can be synthesized from syngas produced via gasification of solid biomass. The selected process is based on the CFB gasification technology [13].

Biomass is gasified at pressurised CFB gasifier operated at ca. 5 bar and 900°C. Product gas is cooled to 550°C, filtered and led into catalytic reformer where tars and hydrocarbon gases are reformed. Then product gas is cleaned, conditioned and pressurised to fuel synthesis. For 2020, a target case is assumed based on hot-filtration of dusty tar-laden product gas at the gasifier's outlet temperature without prior cooling. For 2030, another target case is assumed, again based on hot-filtration of dusty tar-laden product gas at the gasifier's outlet temperature without prior cooling, including gasification taking place at 22 bar. The synthesis of methanol takes place within a quasi-isothermal (around 250°C) reactor technology at 80 bar. The produced methanol will then be purified via a two-stage separation approach based on distillation [13].

Table 14 presents the technical specification of biomass gasification process for methanol synthesis. As feedstock wood pellets as well as pruning & thinning wood have been considered.

Table 14: Technical specification of biomass gasification process for methanol synthesis

	Unit	Value
Biomass input	MW _{th}	300
Conversion efficiency methanol	GJ/GJ biomass input	60% [13]
Conversion efficiency usable heat	GJ/GJ biomass input	15% [13]
LHV methanol	MJ/kg	19.9
	GJ/m ³	15.7
Density methanol	Kg/m ³	791.4
LHV (wood pellet)	GJ/t _{tar}	17 [6]
LHV (pruning & thinning wood)	GJ/t _{tar}	9 [6]

3.5. Type and amount of feedstock used

Based on the data presented in Table 13 and Figure 6, an estimation has been made for the current demand of Europe for methanol. The demand growth in Europe remains tied to GDP levels and so has very limited prospects in the short term [14]. It is therefore assumed, that the demand in 2020 and 2030 for the Medium scenario would remain equal to the current demand in Europe (see Table 15).

Table 15: Current and expected production for methanol in Europe

	Unit	Value
Current global production (2013E)	kt	64575 [12]
EU demand (2013E)	%global	12% [12]
	kt	7749
EU expectation 2020 (Medium Scenario)	kt	7749
EU expectation 2030 (Medium Scenario)	kt	7749
Low Scenario 2020	%MS	80
High Scenario 2020	%MS	120
Low Scenario 2030	%MS	50
High Scenario 2030	%MS	150

Table 16 presents current and expected production of methanol via gasification of solid biomass, based on assumed replacements of 1% resp. 5% in 2020 resp. 2030. Finally, taking the conversion efficiency of methanol synthesis into account, Table 17 presents the amount of biomass required for the methanol PMC.

Table 16: Current and expected production of methanol via gasification of solid biomass

	Unit	Value
Current production	kt	0
Replacement fossil-based methanol in 2020	%	1%
Replacement fossil-based methanol in 2030	%	5%
Expectation 2020 (Medium Scenario 2020)	kt	77
Expectation 2030 (Medium Scenario 2030)	kt	387

Table 17: Total biomass demand for methanol PMC

	Current	2020		2030	
	kt _{air} /a	kt _{air} /a	PJ	kt _{air} /a	PJ
Wood pellets					
Low Scenario	0	121	2.1	378	6.4
Medium Scenario	0	151	2.6	756	12.9
High Scenario	0	181	3.1	1134	19.3
Pruning and thinning wood					
Low Scenario	0	228	2.1	714	6.4
Medium Scenario	0	286	2.6	1428	12.9
High Scenario	0	343	3.1	2142	19.3

4. Hydrogen

4.1. Applications

Many industrial processes require hydrogen as an ingredient, or produce hydrogen as a byproduct. Major industrial consumers of hydrogen are the refinery sector, ammonia industry, hydrochloric acid, methanol, and metal industries.

Many expect hydrogen to play an important role in decarbonizing of the transport sector in the long-term, as it can be derived from many renewable sources including biomass and water.

Table 18: Hydrogen product market combination

Interm. product	Interm. market	Final product	Final Market
Hydrogen	(Petro)chemical industry	Hydrogen	Transport sector
Hydrogen	(Petro)chemical industry	Hydrogenates	Transport sector
Hydrogen	(Petro)chemical industry	Ammonia	Chemical industry
Hydrogen	(Petro)chemical industry	Hydrochloric acid	Chemical industry

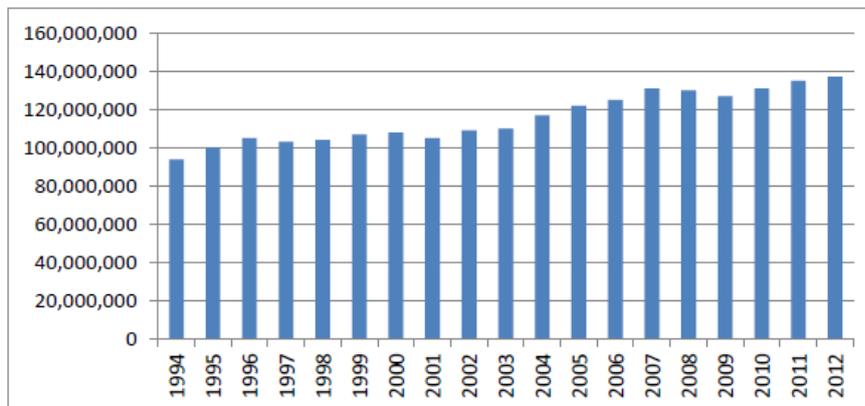
4.2. Market

The main three players in hydrogen market are [15]:

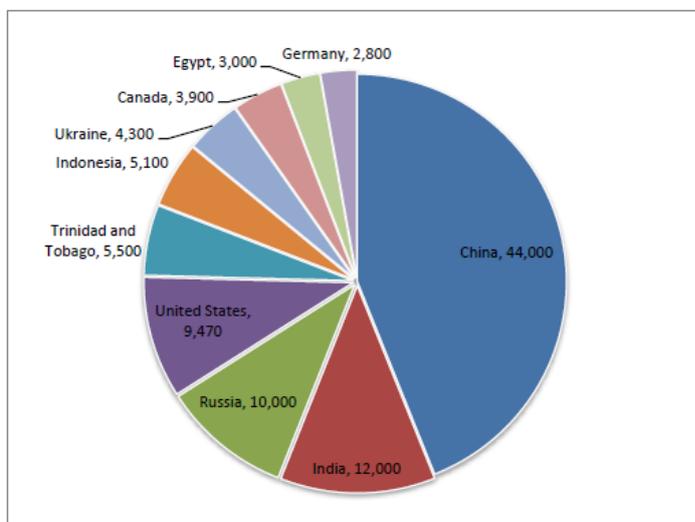
- Merchant companies (which trade hydrogen);
- Captive producers (which produce hydrogen for their direct customer or their own use);
- and byproduct hydrogen producers (which provide hydrogen resulting from chemical processes).

The total European hydrogen production is estimated at about 90 billion m³. Broken down to market sectors, the captive industry produces around 64% of the total, followed by the byproducts industry (27%) and merchant companies (9%).

Global ammonia production has been constantly growing in the last decades, peaking at 137 million tonnes in 2012 (Figure 8).

Figure 8: Global ammonia production (tonnes) [16]


The global production of ammonia is dominated by China which was responsible for 32% of the total global production in 2012; the other major producers are India (9%), US (7%) and Russia (7%). Figure 9 illustrates the ammonia production of the top ten global producers [16].

Figure 9: Top ten global ammonia producers, 2012 [16]


The abundant use of ammonia in fertilizers and agricultural products is expected to drive the global market. Moreover, the large production capacities in China are expected to make Asia Pacific one of the key market segments in the ammonia market. Regions like Russia, Germany, Ukraine, and other East-European countries contribute to making Europe the other major market segment in the ammonia market. The growth in fertilizer production and demand is expected to be the primary driver for the growth in the ammonia market. Acting as a vital source of nitrogen, which is a necessity for plant growth, it promises strong demand in the near future. Also, ammonia acts as a raw material for the preparation of nitric acid which is further used in the production of explosives. Refrigeration is another important application of ammonia, where it is used for cold storage, food preservation, and beverage

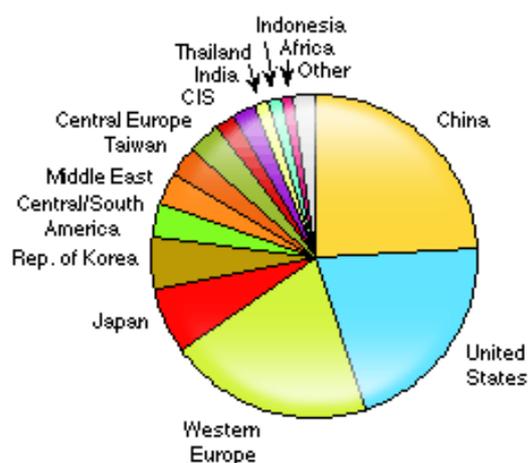
production. However, modest growth in other application segments of ammonia like livestock, pharmaceuticals, plastics industry, paper industry, food industry, and chemicals among others, is expected to augment the demand in the near future [16].

Total world production of hydrochloric acid (in 2005) is estimated at 20 million tonnes (expressed as 100 wt.% HCl). 17 million t/a is produced as a secondary product from organic synthesis and the rest is made from direct synthesis. Most of all hydrochloric acid is consumed on site by the producer. Open world market size is estimated at 5 million t/a [17].

Globally, nearly 67% of all HCl consumption is for the production of ethylene dichloride (EDC) which is cracked to make vinyl chloride monomer (VCM), and over 74% is used in the production of organic compounds, most of which is captive consumption. The remaining consumption is in a number of inorganic or merchant applications [18].

Figure 10 shows the world consumption of hydrochloric acid. With the exception of China and Indonesia, growth in consumption of HCl in Asian countries is small or declining. Canada is projected to have the largest growth at about 10.0% annually during 2011–2018, led by consumption in oil and gas processing and ore/mineral processing, although from a much smaller base. The largest growth rates of higher-consumption regions include the Middle East at 5.5%, Central and South America at 5.4%, Indonesia at 4.3%, Central Europe at about 4.0%, Africa at 3.5% and China at 2.8% [18].

Figure 10: World consumption of hydrochloric acid-2012 [18]



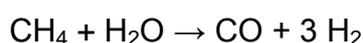
The chlorine industry, including the production, sale and consumption of derivatives such as hydrochloric acid and anhydrous hydrogen chloride, has been under pressure as a result of evidence that several chlorine-containing products are harmful to the environment, to workers and to the general public. Concern over the depletion of the earth's ozone layer associated with the release of chlorofluorocarbons (CFCs)

into the atmosphere resulted in worldwide agreements at the 1987 Montreal Protocol and subsequent meetings to phase out emissions of ozone depleting compounds [18].

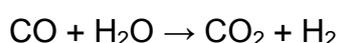
4.3. Reference (fossil) production routes

Currently, the majority of hydrogen (~95%) is produced from fossil fuels by steam reforming or partial oxidation of methane and coal gasification with only a small quantity by other routes such as biomass gasification or electrolysis of water [19].

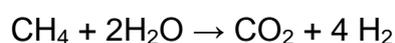
Hydrogen can be generated from natural gas with approximately 80% efficiency, or from other hydrocarbons to a varying degree of efficiency. Specifically, bulk hydrogen is usually produced by the steam reforming of methane or natural gas. At high temperatures (700–1100°C), steam reacts with methane in an endothermic reaction to yield syngas [19].



In a second stage, additional hydrogen is generated through the lower-temperature, exothermic, water gas shift reaction, performed at about 360°C:



With the overall reaction:



4.4. Biobased production routes

Hydrogen can be produced via the following biobased routes [1]:

- Biological routes, such as fermentation of biomass to hydrogen or anaerobic digestion with methane reforming;
- High-temperature gasification of biomass to syngas, followed by a secondary process consisting of water-gas shift reaction and hydrogen separation;
- Low-temperature gasification of biomass to product gas, followed by reforming the methane content of the product gas to additional hydrogen in the product gas, followed by hydrogen separation;
- bio-photochemical conversion of photosynthetic micro-organisms, like microalgae and bacteria.

Biobased hydrogen production routes have the following development status [1]:

- Biogas reforming is at the demonstration phase to early commercialisation;
- Gasification with reforming is at the early stage of demonstration;

- All other novel routes are at the basic and applied R&D phase.

Depending on the conversion routes, the following feedstocks are applied [1]:

- Anaerobic digestion: biodegradable MSW, sewage sludge, manure, wet wastes (farm and food wastes), and macro-algae;
- Gasification: lignocellulosic biomass (wood, staw, energy crops, MSW, etc.);
- Bio-photochemical routes: photosynthetic micro-organisms, like microalgae and bacteria.

4.5. Type and amount of feedstock used

As a biobased route for the production of hydrogen, we focus on the gasification of solid biomass. A conversion efficiency of 60% to hydrogen has been assumed. As feedstock wood pellets as well as pruning & thinning wood have been considered (Table 19).

Table 19: Technical specification of biomass gasification process for hydrogen production

	Unit	Value
Conversion efficiency hydrogen	GJ/GJ biomass input	60%
LHV hydrogen	MJ/m ³	10.8
	MJ/kg	120
LHV (wood pellet)	GJ/t _{ar}	17 [6]
LHV (pruning & thinning wood)	GJ/t _{ar}	9 [6]

Table 20 presents current and expected production of hydrogen in Europe. It is assumed, that for 2020 10% more hydrogen would be required than the current production, due to increased hydrotreating at refineries and as fuel in the transport sector. For 2030 20% more hydrogen would be required, again due to increased hydrotreating, as well as fuel in the transport sector, but also as fuel to be used in fuel cells for stationary application.

Table 20: Current and expected production of hydrogen in Europe

	Unit	Value
Current global production	Nm ³ /a	7.0E+11 [20]
	PJ	7560
Current (2007) EU production	Nm ³ /a	9.0E+10 [15]
	PJ	972
EU expectation 2020 (Medium Scenario)	PJ	1070
EU expectation 2030 (Medium Scenario)	PJ	1170
Low Scenario 2020	%MS	80
High Scenario 2020	%MS	120
Low Scenario 2030	%MS	50
High Scenario 2030	%MS	150

Table 21 presents current and expected production of hydrogen via gasification of solid biomass, based on assumed replacements of 0.1% resp. 1% in 2020 resp. 2030. In order to have a feeling about the expected amount of bio-hydrogen for 2020 and 2030, we assume that the whole amount of 1.1 resp. 11.7 PJ would be used as fuel for hydrogen vehicles. With an average annual mileage of 11000 km/a, and an average hydrogen consumption of 1 kg/100km, about 75,000 resp. 1 million hydrogen vehicles can be fuelled with the produced bio-hydrogen in 2020, resp. 2030.

Table 21: Current and expected production of hydrogen via gasification of solid biomass

	Unit	Value
Current production	PJ	0
Replacement fossil-based hydrogen in 2020	%	0.1%
Replacement fossil-based hydrogen in 2030	%	1%
Expectation 2020 (Medium Scenario 2020)	PJ	1.07
Expectation 2030 (Medium Scenario 2030)	PJ	11.66

Finally, taking the conversion efficiency of hydrogen production into account, Table 22 presents the amount of biomass required for the hydrogen PMC.

Table 22: Total biomass demand for hydrogen PMC

	Current	2020		2030	
	kt _{air} /a	kt _{air} /a	PJ	kt _{air} /a	PJ
Wood pellets					
Low Scenario	0	84	1.4	572	9.7
Medium Scenario	0	105	1.8	1144	19.4
High Scenario	0	126	2.1	1715	29.2
Pruning and thinning wood					
Low Scenario	0	158	1.4	1080	9.7
Medium Scenario	0	198	1.8	2160	19.4
High Scenario	0	238	2.1	3240	29.2

5. Ethylene

5.1. Applications

Ethylene, which is produced from petrochemical feedstock, is one of the most important platform chemicals in use today. Major final products from ethylene are polyethylene, ethylbenzene, ethylene oxide and ethylene dichloride. (Table 23).

Table 23: Ethylene product market combination

Interm. product	Interm. market	Final product	Final Market
Ethylene	(Petro)chemical industry	Polyethylene	Chemical industry
Ethylene	(Petro)chemical industry	Ethylbenzene	Chemical industry
Ethylene	(Petro)chemical industry	Ethylene oxide	Chemical industry
Ethylene	(Petro)chemical industry	Ethylene dichloride	Chemical industry

5.2. Market

Figure 11 presents the West European ethylene capacity, production and consumption in the period 1994 to 2013 [10]. In 2013, the West European ethylene consumption was 18,982 kt, the ethylene production was 18,521 kt, while the capacity was 23,862 kt. The imports from outside Europe was 543 kt, while exports to outside Western Europe amounted to 94 kt.

Figure 11: West European ethylene capacity, production and consumption 1994-2013 [10]



Figure 12 presents the West European ethylene consumption by derivative in 2013 [10]. 60% of ethylene is used for the production of polyethylene. The remaining 40% is used respectively for the production of ethylene dichloride, ethylene oxide, ethylbenzene, vinyl acetate monomer (VAM), and others (including ethanol and

acetaldehyde). Finally Figure 13 shows the historical West European ethylene consumption by derivative for the period 1994 to 2013.

Figure 12: West European ethylene consumption by derivative 2013 [10]

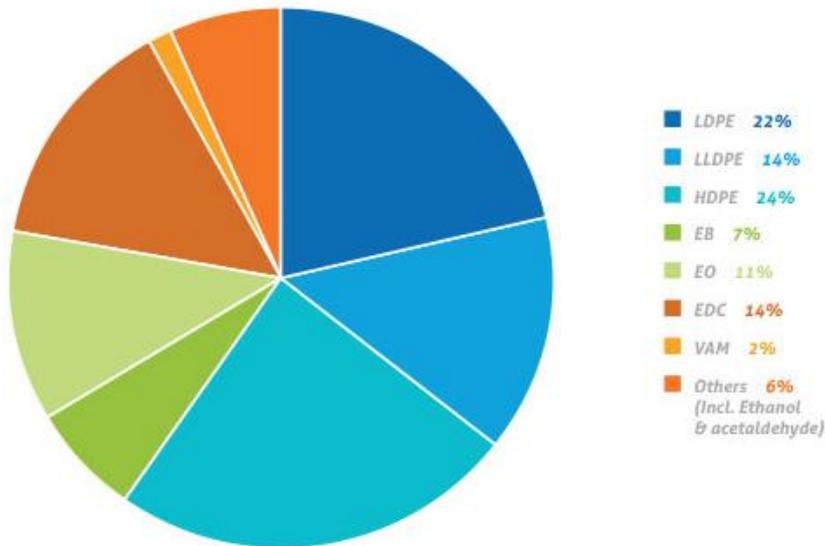
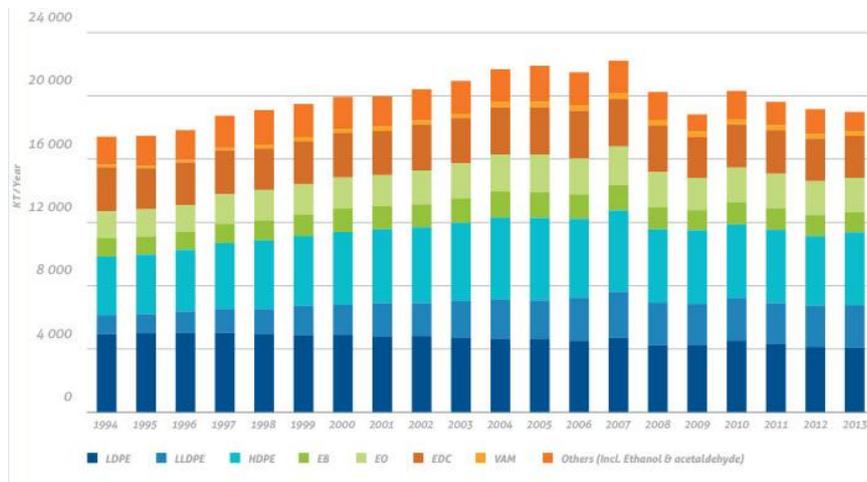


Figure 13: Historical West European ethylene consumption by derivative 1994-2013 [10]

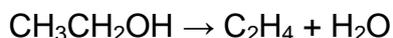


5.3. Reference (fossil) production routes

In Europe and Asia, ethylene is produced mainly from cracking naphtha, gas oil and condensates, with the co-production of propylene, C4 olefins and aromatics from pyrolysis gasoline (pygas).

5.4. Biobased production routes

Ethylene can be produced via dehydration of bioethanol:



Bio-ethylene made from bioethanol represents a chemically identical alternative to ethylene. Compared to the petrochemical equivalent, the main advantages of bio-ethylene are that it can reduce greenhouse gas (GHG) lifetime emissions (from both production and use) and the dependence of the chemical industry on fossil fuels. Bioethanol can be obtained by fermentation of sucrose feedstock (e.g. sugarcane) and from starchy biomass (e.g. corn) by hydrolysis followed by fermentation. These two production routes are well-developed and used to produce bioethanol for the transport sector in countries and regions (e.g. Brazil, the U.S., Europe and China). Besides sugarcane and corn, lignocellulosic biomass can also be used as a feedstock, but the conversion into bioethanol is more challenging and costly due to the biomass chemical structure. If technology advances overcome these issues, bioethanol and bio-ethylene production from lignocellulosic biomass could become economically attractive. In Brazil, bio-ethylene production is already economically competitive due to the ample availability of cheap sugarcane feedstock, extensive experience in ethanol production and increasing oil prices. This has led to new sugarcane-based bio-ethylene capacity. A new plant producing 200 kt per year is already in operation [21].

For Europe we consider the production of bio-ethylene from lignocellulosic biomass, such as wood or straw. These processes, however, still need a full commercial demonstration.

Straw is pre-hydrolyzed to a slurry containing, among others, sugars, cellulose, lignin, and other solved and unsolved components. The slurry is then fermented to ethanol in a simultaneous saccharification and co-fermentation step (SSCF). The solid/liquid stream from the fermentation enters a distillation section, where ethanol and other volatile components are stripped out of the slurry. At the top CO₂ and other light components are removed. The mixture of ethanol and water is led to a rectification column, where ethanol is purified to its azeotropic point (95.6 wt.% ethanol), after which it is passed through a dehydration unit (molecular sieves) to reach a purity of 99.6 wt.%. The bottom fraction of the distillation column is passed through a filtration step, where it is separated in a liquid and a solid fraction. The liquid fraction is led to the water treatment section. The unfermented sugars and other soluble organic components (acetic acid, glycerol) are converted to biogas in an anaerobic water treatment unit, followed by aerobic post-treatment. The produced biogas is combusted in gas engines to produce heat and electricity. The solid fermentation residue together with the surplus sludge, formed in the aerobic water treatment unit, are combusted in the burner of a combined heat and power unit, producing heat and

electricity. The heat as well as a part of the generated electricity are used within the process, and the surplus electricity is delivered to the electricity grid. Table 24 presents technical specification of ethanol synthesis via biochemical conversion process of straw [22].

Table 24: Technical specification of ethanol synthesis via biochemical conversion process of straw [22]

	Unit	Value
Biomass (straw) input	MW_{th}	365.6
Glucose	MW_{th}	15.3
LHV _{ar} straw (11 wt.% moisture)	MJ/kg _{ar}	13.6
LHV bioethanol (99.6%)	MJ/kg	26.7
Ethanol, 99.6 wt. %	MW_{th}	139.1
Electricity	MW_e	25
Conversion efficiency ethanol	%LHV _{straw.ar + glucose}	36.5%
Electricity efficiency	%LHV _{straw.ar + glucose}	6.6%
Total process efficiency	%LHV _{straw.ar + glucose}	43.1%

Once bioethanol has been produced and purified to chemical grade, it is converted to bio-ethylene by an alumina or silica-alumina catalyst. One tonne of bio-ethylene requires 1.74 tonnes of (hydrated) bioethanol. Conversion yields of 99% with 97% selectivity to ethylene have been achieved [21].

5.5. Type and amount of feedstock used

Table 25 presents current global production for ethylene, as well as current consumption and production in Western Europe, with the latter two quite close to each other. The expected production for 2020 and 2030 has been assumed to remain equal to the current production, due to the following reasons [23]:

1. New cost-competitive capacity that has come on stream in the last couple of years in the Middle East;
2. The shale gas revolution and its frequently discussed game -changing advantage versus naphtha in the US;
3. It has long been suggested that 2.2-3 Mtonnes of European ethylene capacity should close.

Table 26 presents current and expected production of ethylene via dehydration of bioethanol. Current global production of bio-ethylene is 420 ktonnes [21]. This is 0.3% of the ethylene global production. Current production of bio-ethylene in Europe is zero, and it is not expected to be any production up to 2020. For 2030 it is assumed, that 1% of the fossil-based ethylene would be replaced by bio-ethylene. Table 27 presents the total biomass (straw) demand for the ethylene PMC.

Table 25: Current and expected production of ethylene in Western Europe

	Unit	Value
Current global production	Kt/a	140,000 [21]
Current Western Europe consumption (2013)	Kt/a	18982
Current Western Europe production (2013)	Kt/a	18521
Current Western Europe capacity (2013)	Kt/a	23862
EU expectation 2020 (Medium Scenario)	Kt/a	18521
EU expectation 2030 (Medium Scenario)	Kt/a	18521
Low Scenario 2020	%MS	80
High Scenario 2020	%MS	120
Low Scenario 2030	%MS	50
High Scenario 2030	%MS	150

Table 26: Current and expected production of ethylene via dehydration of bioethanol

	Unit	Value
Current production	Kt/a	0
Replacement fossil-based ethylene in 2020	%	0%
Replacement fossil-based ethylene in 2030	%	1%
Expectation 2020 (Medium Scenario 2020)	Kt/a	0
Expectation 2030 (Medium Scenario 2030)	Kt/a	185
Low Scenario 2030	Kt/a	93
High Scenario 2030	Kt/a	278

Table 27: Total biomass (straw) demand for ethylene PMC

	Current	2020		2030	
	kt _{air} /a	kt _{air} /a	PJ	kt _{air} /a	PJ
Low Scenario	0	0	0	831	11.3
Medium Scenario	0	0	0	1663	22.6
High Scenario	0	0	0	2494	33.9

6. Mixed alcohols

Production of mixed alcohols via gasification of biomass can be seen as a process for thermochemical (as opposed to biochemical) synthesis of lignocellulosic ethanol to replace petroleum-derived fuels.

Biomass is gasified in an indirect gasifier. The produced gas is reformed to convert methane, light hydrocarbons and tars to syngas in a steam reformer. Gases are cooled and scrubbed and then compressed. The compressed clean syngas is mixed with unreacted gases and methanol from the synthesis reactor, and sent to an alcohol synthesis reactor. Syngas is catalytically converted to a mixture of linear aliphatic alcohols. Intermediate and continuing reactions produce multiple byproducts, including methanol, C₃₊ alcohols, other oxygenates, methane, and light hydrocarbons. In addition, CO₂ is produced from syngas via the water-gas shift reaction. CO₂ is removed with an acid gas removal system located within the syngas recycle loop. Alcohol product is cooled/condensed before fractionation. In total, the process is energy-sufficient; that is, all required process heat and electricity are ultimately generated from the biomass source. In addition to the primary product ethanol, a co-product stream of higher alcohols is also available from the mixed alcohol process. These co-products can be used as stationary equipment fuel or can potentially be blended into gasoline following the required specifications [24].

Table 28 presents a typical mixed alcohol synthesis reaction conditions and specified conversions. As can be seen, a 38% per pass total CO conversion is specified. Excluding CO₂, CO is converted to either alcohols or hydrocarbons (methane, ethane). On a CO₂-free basis, the total selectivity to all alcohols is 80% and selectivity to hydrocarbons is 20%. The highest specific selectivities are for ethanol and methanol [25].

No data is found for the conversion efficiency of this process. The process is mostly developed in the USA (NREL), where the major focus lies on renewable alternatives for fossil-based gasoline. An alternative to this process in Europe is ethanol production via biochemical conversion of lignocellulosic biomass.

Table 28: Mixed alcohol synthesis reaction conditions and specified conversions [25]

	Value	Selectivity (CO ₂ -free)
Temperature (°C)	300	
Pressure (bar)	140	
H ₂ /CO ratio	1.2	
mol% CO conversion (per pass) to:		
CO ₂	13.0%	-
CH ₄	4.5%	18%
C ₂ H ₆	0.5%	2%
Methanol	4.1%	16.4%
Ethanol	11.4%	45.6%
Propanol	3%	12%
Butanol	1.0%	4%
Pentanol & higher	0.5%	2%
Total	38%	100%

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