Deep Decarbonisation of the Dutch Chemical Industry:

A Marginal Abatement Cost Curve Analysis for LyondellBasell

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PBL Netherlands Environmental Assessment Agency

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PREFACE

This thesis has been carried out in fulfilment of my master's degree in Energy Science at Utrecht University. It is conducted in conjunction with my internship with the MIDDEN project, lasting between March and September 2020. The MIDDEN project or known as the Manufacturing Industry Decarbonisation Data Exchange Network, is a joint initiative between the Netherlands Organisation for Applied Scientific Research (TNO) and the Netherlands Environmental Assessment Agency (PBL). Broadly supported by the Dutch government and various industry organisations, the MIDDEN initiative aims to build up a data inventory covering the current overview (e.g. products, processes, and current emissions) and the decarbonisation options of Dutch industry. This thesis further my work with the MIDDEN project, by conducting a techno-economic analysis for LyondellBasell, using the marginal abatement cost (MAC) curve methodology.

This thesis could not be completed without the support from many others, particularly my PBL supervisor, Andrew Keys, and my university supervisor, Dr Li Shen. Their consistent support and constructive feedback have kept me motivated to try my best. Many thanks to Ton (ECN) and Dick (PBL) for trusting me with this MIDDEN assignment. They have also made my involvement in the MIDDEN project a great learning experience by organising various meetings and workshops. Also, special thanks to Marc (PBL) for his guidance during the first month, and other MIDDEN members for their help. Starting and finishing this thesis project at the time of the COVID-19 crisis is certainly not ideal, and unfortunately, I wasn't able to make much out of my time with PBL. I am however grateful for the generosity of my host institution, PBL. Receiving a flower bouquet, a haagsche kakker, and a book voucher at unexpected times has made this difficult time more bearable.

It is a bittersweet feeling as I realise my time at Utrecht University and the Netherlands is coming to an end. I will forever remember these wonderful two years I've had here in the Netherlands. My time in Utrecht wouldn't be as amazing if not for my close friends – Alix, Etienne, Duccio, Jan and Florian. Greatest appreciation for my family and my best friend, Daniel Chan, for being supportive of my educational pursuits, morally and financially. Last but not least, I am thankful for the kind donors of Utrecht Excellence Scholarship and Geosciences Scholarship, who have provided me with the financial opportunities to further my education at Utrecht University.

Charlotte Yong
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ABSTRACT

Achieving the climate goals stipulated in the Dutch Climate Agreement requires a collective effort from all sectors, particularly the Dutch industry – a major emissions contributor. This study proposes the most appropriate decarbonisation options in achieving (near) net-zero scope 1 and 2 emissions for a major chemical company – LyondellBasell. Specifically, its production sites in Botlek and Maasvlakte. The *Marginal Abatement Cost (MAC) curve* analysis is utilised as the main analysis method to assess the cost-effectiveness and the abatement potential of seven decarbonisation options. This is complemented with a qualitative discussion on the relevant non-economic factors. Together, providing a comprehensive view of both the cost-effectiveness and the implementation feasibility.

The two production sites, which together has a total of 7 main chemical processes, allow optimised product flows and cascaded steam usage across processes and units, and are integrated with external utility companies – resulted in a considerable amount of scope 2 emissions. This research found that 88% of the total scope 1 and 2 emissions is attributable to its steam consumption of around 8 PJ/year. This translates into annual carbon emissions of 416 kton and 620 kton, for the Maasvlakte and Botlek site, respectively. These present deep decarbonisation opportunities for both scope 1 and 2 emissions, through the decarbonisation of high-temperature steam supply.

The MAC curves concluded that the Post-Combustion Carbon Capture Storage (CCS) options are the most cost-effective. The Complete Post-Combustion CCS configuration has a MAC (considering carbon price) of -33.6 $€_{2018}/tCO_2$ for the Maasvlakte site (79% carbon reduction) and 16.4 $€_{2018}/tCO_2$ for the Botlek site (85% carbon reduction). Followed closely are the hydrogen combustion options with blue or green hydrogen (H_2) and the biomass boiler option. Electricity-dependent technologies are disfavoured due to their high MACs, as the electricity price is projected to increase highly over the analysis period. Nonetheless, the supply scarcity of green H_2 and controversial sustainability issues around biomass supply are likely to hinder the implementation of those options. Coupling with energy transition initiatives put forward for the Port of Rotterdam industrial cluster (i.e. PORTHOS and H-Vision), this research concludes that the Post-Combustion CCS and the hydrogen combustion option with blue H_2 are the most appropriate options for deep decarbonisation, in terms of both cost-effectiveness and implementation feasibility.

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GLOSSARY OF ABBREVIATIONS

AA	Allyl alcohol	**MPD**	Methyl propanediol
ACP	Acetophenone	**MPP3**	Maasvlakte Power Plant 3
AEL	Alkaline electrolysis	**MTBE**	Methyl tertiary-butyl ether
ATR	Auto thermal reforming	**OPEX**	Operating expenditure
BDO	Butanediol	**PBL**	Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)
CAPEX	Capital expenditure	**PEB**	Polyethylbenzenes
CCS	Carbon capture and storage	**PEM**	Polymer Electrolyte Membrane
EB	Ehylbenzene	**PG**	Propylene glycol
EBHP	Ethylbenzene hydroperoxide	**PGME**	Propylene glycol methyl ether
ETBE	Ethyl tertiary butyl ether	**PO**	Propylene oxide
EU-ETS	European Union Emission Trading Scheme	**PORTHOS**	Port of Rotterdam CO_2 Transport Hub and Offshore Storage
GHG	Greenhouse gases	**SM**	Styrene monomer
HAS	Heavy aromatic solvent	**TBA**	Gasoline grade tert-Butyl alcohol
LHV	Lower heating value	**TBHP**	Tertbutyl hydroperoxide
MAC	Marginal abatement cost	**TNO**	Netherlands Organisation for Applied Scientific Research
MBA	Methylbenzyl alcohol	**TRL**	Technological readiness level
MEA	Monoethanolamine	**UCML**	Utility Centre Maasvlakte Leftbank
MIDDEN	Manufacturing Industry Decarbonisation Data Exchange Network	**WLO**	Welvaart en leefomgeving

CHAPTER 1: INTRODUCTION

Pressure has been built upon the national governments to accelerate their climate action to align with the Paris Agreement. The Intergovernmental Panel on Climate Change (IPCC)'s report warns of significant climate-related impacts resulting from global mean temperature rise, emphasising the urgency for deep decarbonisation from all sectors at an unprecedented scale [1]. While limiting the increase in global mean temperature requires a global effort, the Netherlands has taken a stride further by introducing the Dutch Climate Agreement (*Klimaatakkoord*). The Dutch Climate Agreement stipulates the Dutch greenhouse gases (GHG) reduction goal of 49% by 2030 and a 95% reduction by 2050, compared to the 1990 level [2]. Currently, the primary decarbonisation focus is on the power generation sector, with planned moves to phase out existing coal power plants and increase renewable energy capacities. However, this does not go far enough, and more is needed across other sectors. For instance, the manufacturing industry, if the GHG reduction goals are to be achieved.

1.1. MIDDEN INITIATIVE & LYONDELLBASELL

The Dutch industry, as a whole, accounts for 31 % of the total GHG emissions within the Netherlands (on scope 1 basis) [3]. To reach the overarching Climate Agreement [2], a 59% GHG reduction (compared to 1990 level) or a 19.4 Mton reduction (compared to 2015 level) is required from the Dutch industry. In light of such aspiration, scientifically-informed decisions supported by a good understanding of the current industrial processes and the decarbonisation opportunities are imperative in driving sustainable transition in both the short- and long- term. The Manufacturing Industry Decarbonisation Data Exchange Network (MIDDEN) initiative has been jointly set up by the Netherlands Organisation for Applied Scientific Research (TNO) and the Netherlands Environmental Assessment Agency (PBL) [4]. Broadly supported by the Dutch government and various industry organisations, the MIDDEN initiative aims to build up a data inventory covering the current overview (e.g. products, processes, and current emissions) of the Dutch industry and the applicable decarbonisation options. The project scope covers the industries (e.g. steel, paper and board) which are located within the Netherlands and fall under the European Union Emission Trading Scheme (EU-ETS). This up-to-date information aims to benefit the wide range of stakeholders by providing new insights, as well as to guide public decision-making.

This research contributes towards the MIDDEN's initiative by investigating in-depth the decarbonisation opportunities for the Dutch chemical industry. Specifically, decarbonisation opportunities for the processes and operations of one major industrial player – LyondellBasell. The GHG emissions from the chemical industry are significant, making up around 7 % of the total global GHG emissions in 2017 [5]. The chemical industry has a huge presence in the Netherlands, with the Netherlands being the fourth largest chemical producer in Europe, and tenth worldwide [6]. This, in turn, contributes significantly to the Dutch GHG emissions. The scope 1 GHG emissions from the chemical companies total over 19 Mton in 2018 [7], with substantial indirect scope 2 emissions through their integration with the energy sector. For LyondellBasell, the scope 1 CO_2 emissions from its operations in the Netherlands are approximately 350 kton [8]. Though comparatively small, the energy consumption and scope 2 emissions are significant. Hence, decarbonisation efforts on both scope 1 and 2 emissions would have a far-reaching impact in achieving the overarching Dutch GHG reduction goals. Building on top of the MIDDEN initiative, this research sought to identify the most appropriate decarbonisation option(s) in achieving (near) net-zero scope 1 and 2 emissions for LyondellBasell, considering both the cost-effectiveness and implementation feasibility.

1.2. RESEARCH RATIONALE

Achieving the Dutch Climate Agreement is not an easy feat and requires carefully crafted strategies. As stipulated in the Dutch Climate Agreement, several measures have been proposed from both the policy and technological viewpoints [2]. From the technological perspective, it is envisioned that green hydrogen and carbon capture and storage (CCS) will play a significant role in the overall industrial decarbonisation effort. In addition to that, a high-level decarbonisation roadmap for the chemical industry to achieve the 2030 and 2050 reduction goals has been jointly presented by the Royal Association of the Dutch Chemical Industry (VNCI), Ecofys and Berenschot. The study took a top-down approach to assess the different technological pathways and respective investment and material costs for the chemical industry, as a whole [9]. Other decarbonisation scenarios, such as on the use of electrification in the European Union chemical industry [10–11], as well as on the industrial level cluster level (i.e. Rotterdam) were also studied [12].

The Dutch chemical industry spans a wide range of products. Furthermore, due to spatial complexity and current inter- and intra- industrial synergies, decarbonisation opportunities and barriers shall differ across processes and locations. Sectoral studies are useful for overarching industrial strategies; however, they lack the information for targeted decision-making and concrete decarbonisation actions. These are to be supplemented with bottom-up plant- or process-specific decarbonisation studies. However, such knowledge is currently lacking in the public domain. This leads to huge knowledge uncertainties and hinders evidence-based policymaking. Hence, this research sought to address the research gap to attentively improve on the plant and process-specific knowledge of LyondellBasell, subsequently identify the relevant decarbonisation opportunities. Taking from there, this research attempts to conclude the most-appropriate decarbonisation option(s) for LyondellBasell, through the performance of marginal abatement cost (MAC) curve analysis. Subsequently, followed by a quantitative discussion on the non-economic factors. The main research objective and sub-objectives are outlined in 1.4.

1.3. RESEARCH SCOPE

LyondellBasell has in total of three production sites and a deep-water terminal in the Netherlands. The research scope is, however, limited to two of LyondellBasell's production sites. The production sites within the scope are:

- Rotterdam/Botlek: Lyondell Chemie Nederland B.V.
- Rotterdam/Maasvlakte: LyondellBasell Covestro Manufacturing Maasvlakte V.O.F

The scoping is made based on the magnitude of the sites' economic impacts (see Table 1), which are substantially larger than the Moerdijk site. An overview of LyondellBasell's operations in the Netherlands is provided in 3.1, and the two production sites are further introduced in 3.1.1 and 3.1.2.

1.4. RESEARCH OBJECTIVE

The main research objective is to identify the most-appropriate decarbonisation option(s) for LyondellBasell's operations at the Botlek and Maasvlakte sites, in achieving deep decarbonisation (for both scope 1 and 2 emissions), at the reference year of 2030.

To fulfil the main research objective, this research employed the marginal abatement cost (MAC) curve methodology as the main quantitative analysis method, to assess the cost-effectiveness and the abatement potential of the decarbonisation options. Subsequently, complemented by a qualitative discussion on the

implementation feasibility concerning the non-economic factors, as well as the general decarbonisation direction of the Port of Rotterdam and the Netherlands. To do so, this research has first gathered an understanding of LyondellBasell's operations to identify the emission hotspots. The following specifies several sub-objectives in chronological order, which facilitated this research in meeting the main research objective:

1. Gain understanding of the current product processes and quantitatively determine the mass & energy flows, as well as the scope 1 and 2 CO_2 emissions.
2. Based on results of sub-objective 1, determine the main emission hotspots (i.e. energy usage, process-related emissions) and prioritise the decarbonisation focus.
3. Prioritise a limited number of promising decarbonisation options to the decarbonisation focus, taking into account several selection constraints.
4. Perform two separate MAC curve analyses for the Botlek and Maasvlakte production site to assess the technical abatement potential and cost-effectiveness of the prioritised decarbonisation options.
5. Critically assess the implementation feasibility of the decarbonisation options, based on their cost-effectiveness, non-economic constraints, whilst taking into account the sensitivity of the results depending on a number of key parameters.

CHAPTER 2: RESEARCH METHODOLOGY

This research was conducted in four main successive phases to address the research main and sub-objectives detailed in 1.4. The research flow is as illustrated in Figure 1. In short, the research phases involved stages of extensive literature review and quantitative-qualitative analysis in assessing the cost-effectiveness and the implementation feasibility of the decarbonisation options to achieve (near) net-zero scope 1 and 2 emissions.

Formal consultation and validation checkpoints were initially planned to seek LyondellBasell's feedback and validation on the gathered results, as well as to understand the industry's perspective with regard to the decarbonisation options. Unfortunately, LyondellBasell was unable to provide further insights due to legal confidentiality reason. In light of such constraint, a number of assumptions were made based on outdated and/or indirect sources, for areas where direct public data is not readily available. The results and information accuracies, particularly on their current process situations, are hence undefined.

Each research phase is further elaborated in the following subsections.

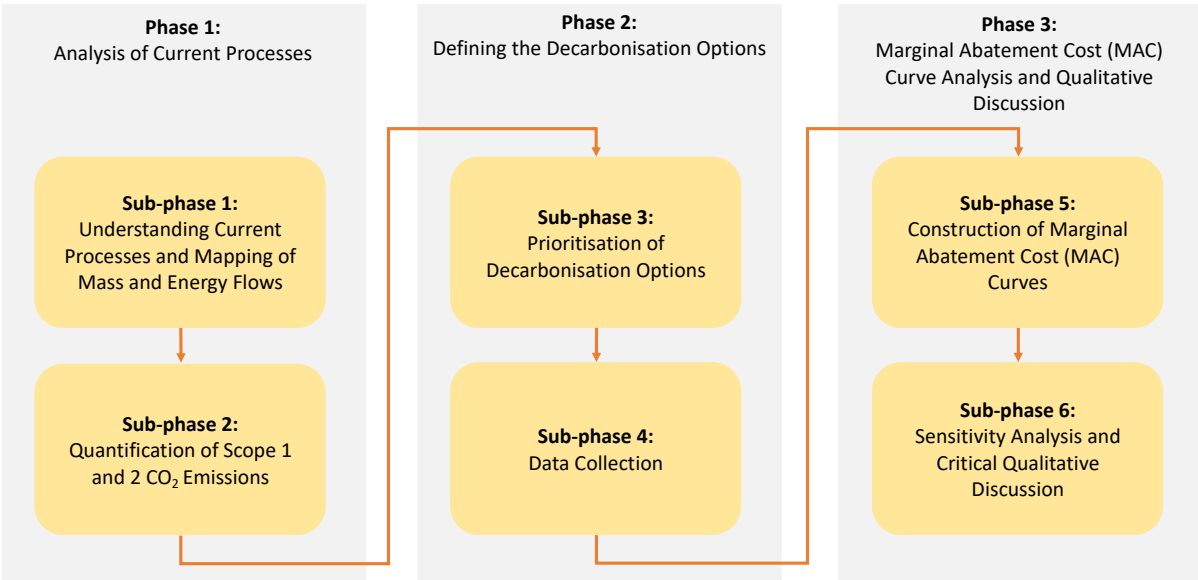

Figure 1: Diagram showing the research flow

2.1. PHASE 1: ANALYSIS OF CURRENT PROCESSES

2.1.1. SUB-PHASE 1: UNDERSTANDING CURRENT PROCESSES AND MAPPING OF ENERGY AND MATERIAL FLOWS

This research first gathered a general understanding of the current operations and the production processes in the Botlek and Maasvlakte production sites through an extensive review of publicly available sources. The site-specific information is such as the site expansion history, production capacity, energy logistics (i.e. steam and electricity input from external parties) and existing infrastructures on-site. Process-specific information includes a general description of the production processes, energy (i.e. steam and electricity) and material flows. The data collection for the process-specific information has prioritised the site-specific and

LyondellBasell-specific information (i.e. [13]) to better reflect the actual operations. Nonetheless, the majority of the process-specific information is however based on generic sources.

2.1.2. SUB-PHASE 2: QUANTIFICATION OF SCOPE 1 AND SCOPE 2 CO_2 EMISSIONS

The scope 1 and 2 carbon emissions from the two production sites were quantified based on site-specific and process-specific data gathered in sub-phase 1.

2.2. PHASE 2: DEFINING DECARBONISATION OPTIONS

2.2.1. SUB-PHASE 3: PRIORITISATION OF DECARBONISATION OPTIONS

Following the quantification of carbon emissions for both production sites, it is noted that steam consumption has the most significant contribution to the overall emissions. It is hence decided that the decarbonisation focus shall be on steam usage. A few constraints have been applied while shortlisting the most-promising decarbonisation options for the MAC curve analysis. The constraints have excluded 1) alternative processes in producing the same chemical products, 2) process-specific options and further heat integration options and 3) technologies that have yet reached commercial maturity. These constraints are further explained using LyondellBasell's context in Chapter 5. The prioritisation of steam decarbonisation options also took into account existing facilities on-site (i.e. gas-fired steam boilers), as well as initiatives promoted at the Port of Rotterdam industrial cluster. Besides, this research considered only LyondellBasell's decarbonisation effort in reducing its scope 1 and scope 2 emissions.

2.2.2. SUB-PHASE 4: DATA COLLECTION

An extensive literature search was then conducted to collect the relevant technical and economic data pertaining to the prioritised decarbonisation options. While doing so, data most relevant for the Netherlands and reflect the possible technical and economic advancements for the year 2030 were collected, whenever possible.

2.3. PHASE 3: MARGINAL ABATEMENT COST (MAC) CURVE ANALYSIS AND DISCUSSION

2.3.1. SUB-PHASE 5: CONSTRUCTION OF THE MAC CURVES

The marginal abatement cost (MAC) curve methodology is chosen as the methodology of choice for this research due to its ability to provide straightforward comparison between options, based on their cost-effectiveness and abatement potential. The MAC curve analyses were conducted separately for the two production sites. The MAC curve analysis employed the "frozen-technology" baseline as the reference situations. Meaning, the reference situations assumed no technological changes on both the supply and demand sides between current, the analysis base year and well into the end-year of the analysis. To further explain, the energy intensities and the production capacities of the processes are assumed to be temporally constant. In addition, there are also no changes to the source of energy input, hence the emissions, for both the Botlek and Maasvlakte site. The reference situations are summarised in 4.1.3 and 4.2.7, as well as in Figure 16. Year 2029 has been chosen as year 0 or investment year and 2030 as the start of operation for the analyses, with the assumption that majority of the investment decisions only occur in conjunction with

the 2030 climate target stipulated in the Climate Agreement. The technical and economic performances of the decarbonisation options were assessed for the construction of MAC curves, as follows.

Technical Performance – Abatement Potential

The abatement potential, in terms of tonne of CO_2 per year, of the decarbonisation option was assessed with reference to the energy technology it is replacing. It is taken as the yearly average of the total CO_2 abatement over its technical lifetime. This formula, hence, takes into account the expected decrement in electricity grid emission, due to increasing penetration of renewable sources over time. The yearly decreasing electricity grid emission factor is used in quantifying the abatement potential of blue hydrogen and carbon capture and storage (CCS) technologies. For technologies requiring electricity as primary fuel input, the electricity emissions are assumed to be zero. These technologies are electrode boiler and the production of hydrogen using on-site Polymer Electrolyte Membrane (PEM) or Alkaline Electrolysis (AEL) technologies. Notwithstanding, this requires the purchasing of Guarantee of Origin (GoO) certificates or the arrangement of Power Purchasing Agreement (PPA), before the national power grid is fully decarbonised. The emission factors for the different other fuels are listed in Appendix A.4.

$$\Delta CO2_{av.} = \frac{\Delta CO2_{Lifetime}}{T} = \frac{\sum_{t=1}^{T} \Delta CO2_t}{T} = \frac{\sum_i \sum_{t=1}^{T} F_{i,ref} * EF_{i,t} - \sum_i \sum_{t=1}^{T} F_{i,D} * EF_{i,t}}{T}$$

$\Delta CO2_{av.}$	= abatement potential (tCO_2/year)
$F_{i,ref}$	= Fuel consumption (or steam consumption, for the case of Maasvlakte) for fuel i for the reference technology (PJ)
$EF_{i,t}$	= Emission factor for fuel i at year t (kton/PJ)
F_D	= Fuel (or electricity) consumption for fuel i for the decarbonisation option
T	= technical lifetime of the decarbonisation option

Economic Performance – Marginal Abatement Cost

The marginal abatement cost (MAC), in terms of $€_{2018}$ per tonne of CO_2, for the decarbonisation option was calculated with reference to the technology it is replacing. As abovementioned, the electricity utilised in three of the technologies is assumed to be zero emissions, requiring the purchase of GoO certificates or the arrangement of PPA. These additional costs were not considered while performing the marginal abatement cost calculation[1]. Two sets of marginal abatement costs were calculated for the main results in Chapter 6, including and excluding the carbon price. Inclusion of carbon price hence treats the mitigated carbon emissions as a form cost-saving, either as avoided carbon penalty or revenue in selling the now-surplus carbon certificates. This is to explore how carbon prices may influence the cost-effectiveness of the options. The discount rate r is assumed to be 6% in the baseline results. The fuel and carbon prices are as shown in Appendix A.4. The 2030 fuel and carbon prices are as projected in [14], while the 2050 prices are as projected in the WLO High Scenario [15]. The fuel and carbon prices between the two reference points and beyond 2050 were linearly interpolated and extrapolated. The O&M cost for the reference technology used in the Botlek production site assumed the O&M cost for a natural gas boiler, as listed in Table 39.

[1] The exclusion of such additional costs is further discussed in the discussion section (see Chapter 7: Sensitivity Analysis & Discussion).

$$MAC = \frac{NPC}{\Delta \mathrm{CO2}_{\mathrm{lifetime}}}$$

$$NPC = I + \sum_{t=1}^{T} \frac{\Delta O\&M_{D-ref} + \sum_i (\Delta F_{i,D-ref} * FP_{i,t}) - (\Delta \mathrm{CO2}_{\mathrm{t}} * CP_t)}{(1+r)^t}$$

MAC	= Marginal abatement cost (€$_{2018}$/tCO_2)
NPC	= Net present cost (€$_{2018}$)
I	= Investment cost (€$_{2018}$)
$\Delta O\&M_{D-ref}$	= net change in operational and maintenance costs (€$_{2018}$)
$\Delta F_{i,D-ref}$	= net change in fuel consumption for fuel *i* (or steam consumption) (GJ)
$FP_{i,t}$	= Fuel price for fuel *i* (or steam consumption) at year t (€$_{2018}$/GJ)
CP_t	= Carbon price at year t (€$_{2018}$/tCO_2)
r	= discount rate

2.3.2. SUB-PHASE 6: SENSITIVITY ANALYSIS AND CRITICAL QUALITATIVE DISCUSSION

Blanket sensitivity analyses were conducted on a few key parameters, namely the discount rate and the fuel and carbon price assumptions based on WLO Low Scenario. Additionally, the influence of highly uncertain technology-specific parameters (i.e. technical lifetime for hydrogen retrofit, CCS processing tariff) on the results were further assessed. Given the limitations of a MAC analysis in assessing non-economic factors (as further explained in 7.2), the results were critically discussed based on relevant non-economic factors, for instance, resource availability and policy restrictions.

CHAPTER 3: BACKGROUND

3.1. LYONDELLBASELL IN THE NETHERLANDS

LyondellBasell is one of the largest chemical companies in the world, with saleable products including chemicals, polymers, fuels, and technologies. As a multinational company, its operations are widespread across the globe with manufacturing facilities in America, Europe and Asia [16]. In the Netherlands, LyondellBasell has in total of three manufacturing facilities and a deep-water terminal (i.e. Europoort Terminal). These operating facilities are all located within the Port of Rotterdam industrial cluster, as shown in Figure 2. Table 1 summarises the three manufacturing sites in terms of its economic impact, site area, employee number and the scope 1 CO_2 emissions as registered with the Dutch Emission Authority [8].

Figure 2: Locations of LyondellBasell's operating sites in Maasvlakte, Europoort and Moerdijk, relative to the City of Rotterdam [17].

Table 1: Site-specific information in terms of site area, employee number, economic impact and CO_2 emissions on scope 1 basis [8–18–20].

Site	Registered Name	Site Area ('$10^3 m^2$)	Employee Number	Economic Impact (million USD)[2]	CO_2 Emissions (kton)[3]
Botlek	Lyondell Chemie Nederland B.V.	480	435	321	322
Maasvlakte	LyondellBasell Covestro Manufacturing Maasvlakte V.O.F	600	260	321	11
Moerdijk	Basell Benelux B.V.	340	146	50	14

[2] Estimate includes yearly total for goods & services purchased and employee pay and benefits, excluding raw materials purchased (basis 2016)

[3] Emission figures for 2019 [8]

LyondellBasell's reported emissions only account for 2% of the overall scope 1 emissions from the Dutch chemical industry. However, these emission figures only include the scope 1 emissions, hence there is a significant underestimation of the total CO_2 emissions across the product value chains. LyondellBasell's strategic location at the Port of Rotterdam industrial cluster allows material and utility sharing between the neighbouring companies, through steam and product pipelines. Many of the required utilities (i.e. steam and electricity) and materials are not produced on-site. Hence, its scope 2 and scope 3 emissions are significant. The "missing" emissions, specifically the electricity and process heat-related scope 2 emissions, are quantified based on the energy consumption and assumed emission factors. These are documented in 4.1.3 and 4.2.7.

This research focuses only on the Botlek and Maasvlakte production sites. The two sites are described further in the following subsections.

3.1.1. MAASVLAKTE SITE

The Maasvlakte production site started its operations in 2003 and is a joint venture between LyondellBasell and Covestro (formerly called Bayer MaterialScience). The two companies each own 50 per cent of the plant and its production, with LyondellBasell acting as the operator. The site houses other different functional buildings such as storage park, laboratory, office building and maintenance workshops. In addition, there are also on-site rail track and truck terminal and a deep sea harbour [20]. The location of the production site within the Maasvlakte region is as shown in Figure 3.

Figure 3: (Left) LyondellBasell's Maasvlakte site within the Maasvlakte region. (Right) LyondellBasell's Maasvlakte site relative to UCML and Neste. Both images are sourced and adapted from [21].

The Maasvlakte site has only two main end-products – propylene oxide (PO) and styrene monomer (SM), produced using its proprietary PO/SM technology. The PO/SM plant is also currently the largest in the world. Table 2 shows the two products manufactured at the Maasvlakte site and their respective annual production capacity. It is also noted in [22], a large portion of LyondellBasell's share of PO is used to supply feedstock to the BDO plant at the Botlek site.

Table 2: Products manufactured at the Maasvlakte site and their respective annual production capacity in kton, as estimated based on [23–24].

Product	Annual Production Capacity (kton)
Propylene Oxide (PO)	385
Styrene Monomer (SM)	864

3.1.2. BOTLEK SITE

This production site has the longest history out of all LyondellBasell's operations in the Netherlands. Located in Botlek, Rotterdam, it has an independent harbour and site-owned train and truck terminal. It is also linked to the Maasvlakte production site by two 7 km pipelines [18]. Figure 4 shows the location of the production within the Botlek region, as well as relative to a few important stakeholders of LyondellBasell's operations within the Rotterdam region, i.e. WKC Air Products and Eurogen C.V.

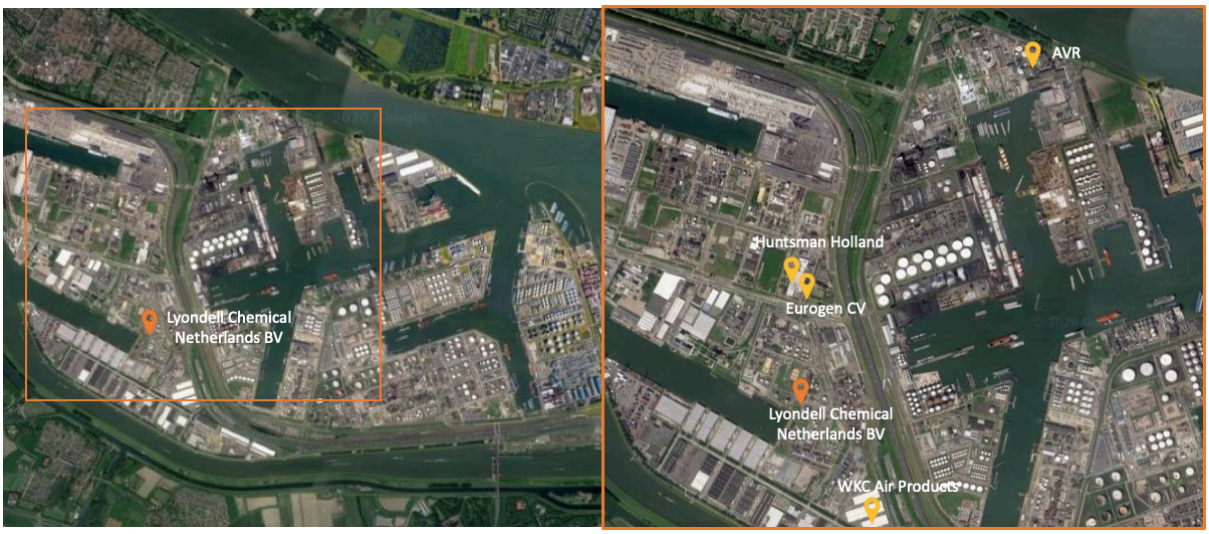

Figure 4: (Left) LyondellBasell's Botlek site within the Botlek region. (Right) LyondellBasell's Botlek site relative to other relevant industrial sites. Both images are sourced and adapted from [21].

The facility was first built in 1972, producing propylene oxide (PO) and tert-Butyl alcohol (TBA) through its proprietary PO/TBA technology. The site has since expanded in 1980 to also produce C4 (i.e. isobutylene), propylene glycol (PG), propylene glycol methyl ether (PGME), Methyl Tertiary-Butyl Ether (MTBE) and Ethyl Tertiary Butyl Ether (ETBE). In 2002, it became equipped with the world's largest Butanediol (BDO) plant. The most recent expansion was in 2015, which saw an increase in butane isomerisation capacity and the addition of two on-site steam boilers [18]. Table 3 shows the whole suite of products produced in the Botlek production site [23]. Some of the products are intermediate or by-products of the main production processes. At the same time, some are used as input materials for the other processes. The material relationships between the different processes are further described in 4.2 and as illustrated in Figure 9.

Table 3: The suite of products manufactured at the Botlek site and their respective annual production capacity in kton [23]

Product	Annual Production Capacity (kton)
Propylene Oxide (PO)	250
Propylene Glycol (PG)	80
Propylene Glycol Methyl Ether (PGME)	90
Tertbutyl Hydroperoxide (TBHP)	12
Methyl Tertiary-Butyl Ether (MTBE)/ Ethyl Tertiary Butyl Ether (ETBE)	400
Gasoline grade tert-Butyl alcohol (TBA)	589
Isobutylene	100
Butanediol (BDO)	126
Allyl alcohol (AA)	16
Methyl propanediol (MPD)	20

CHAPTER 4: CURRENT PROCESSES

Chemical processes are generally energy-intensive and require a substantial amount of heat and electricity. Processing heat is mainly used in maintaining the reaction temperature and for distillation purposes, while electricity is used to power the compressors and pumps. Nonetheless, the different chemical processes differ in their energy intensity, depending on the type of reaction, required operating temperature and pressure, and process equipment required. Accordingly, the chemical processes present in LyondellBasell's operations in the Netherlands contribute at different proportions to the overall energy use and CO_2 emissions. In addition to that, chemical processes also typically produce a substantial amount of waste fuel streams, resulted from low conversion efficiency and low product selectivity.

This chapter will elaborate on the main chemical processes present in both production sites in Maasvlakte and Botlek. The elaboration includes a process description of the processes, as well as their respective energy and material flows. Besides, the main external utilities supplied to LyondellBasell are identified and described. On an important note, neither the material and energy flows of the chemical processes nor any other information of LyondellBasell's operations were verified by LyondellBasell. The annual energy consumption, as well as scope 1 and 2 carbon emissions of the two production sites, are estimated and presented later in this chapter.

4.1. CURRENT PRODUCTION PROCESSES IN MAASVLAKTE

LyondellBasell's Maasvlakte operation site produces only two main products: propylene oxide (PO) and styrene monomer (SM) through its proprietary PO/SM co-production technology. The process utilises the ethylbenzene (EB) produced on-site through the benzene alkylation process between benzene and ethylene. The high-level material flow is as illustrated in Figure 5, while the two processes are separately described the later sub-sections.

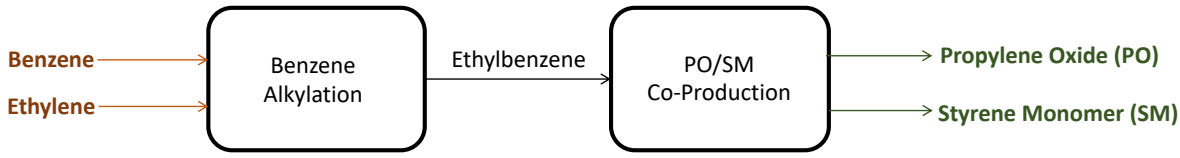

Figure 5: High level material flow in the benzene alkylation and PO/SM co-production processes

The estimated annual amount of energy consumption is quantified in 4.1.3, while the annual amount of material input and waste output are summarised in A.1.

4.1.1. BENZENE ALKYLATION PROCESS

The benzene alkylation process utilises liquid benzene and gaseous ethylene as the raw input materials. It can be further differentiated into three main successive reaction steps: alkylation, ethylbenzene (EB) purification and transalkylation. The process is schematically illustrated in Figure 6. Unless stated otherwise, the process is further elaborated based on [13], of which detailed process description and process flow diagram can be found.

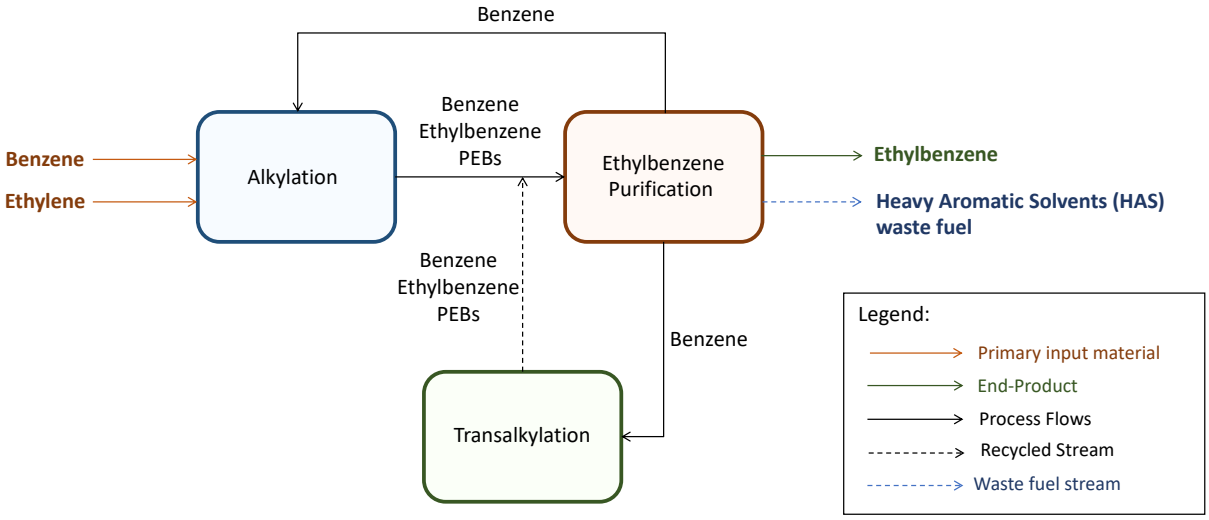

Figure 6: Simplified process flow diagram of the benzene alkylation process

Alkylation

Alkylation is an exothermic reaction between ethylene and benzene into ethylbenzene. In addition, some of the ethylene further react with (di)ethylbenzene to form polyethylbenzenes (PEBs). The liquid phase reaction takes place in two serially-connected reactors at a temperature range between 200°C to 250°C and pressure of 26 to 28 bar(g), in the presence of zeolite catalyst. The alkylation process can be described using the main reaction formulas below:

1) $C_6H_6(Benzene) + C_2(Ethylene) \Longrightarrow C_8H_{10}(Ethylbenzene)$ $\Delta H = -113kJ/mol$
2) $C_8H_{10}(Ethylbenzene) + C_2(Ethylene) \Longrightarrow C_6H_4(C_2H_5)_2\ (Diethylbenzene)$ $\Delta H = -113kJ/mol$
3) $C_6H_4(C_2H_5)_2\ (Dithylenzene) + C_2(Ethylene) \Longrightarrow C_6H_3(C_2H_5)_3\ (Triethylbenzene)$ $\Delta H = -113kJ/mol$

Ethylbenzene (EB) Purification

The effluents from the alkylation unit are then fed into a succession of three distillation columns. The Benzene Column allows the recovery of excess benzene, which is sent to the alkylation unit and the transalkylation unit. The desired product, EB, is recovered from the EB column and later used as input material for the PO/SM co-production process. An EB/PEB stream is recovered from the PEB Column and sent to the transalkylation unit. The bottom product, the heavy aromatic solvent (HAS) stream, is instead exported as fuel.

Transalkylation

Transalkylation reaction is a heat-neutral reaction between PEBs and benzene to form EB. The reaction takes place at around 215 °C and 22 bar(g), in the presence of zeolite catalyst. The effluent from the transalkylation unit containing unreacted benzene and PEBs is again recycled and purified through the distillation columns. The transalkylation process can be described using the main reaction equations below:

1) $C_6H_5(C_2H_5)_2\ (Diethylenzene) + C_2H_6(Benzene) = 2\ C_6H_5(C_2H_5)\ (Ethylbenzene)$
2) $C_6H_5(C_2H_5)_3\ (Dithylenzene) + C_2H_6(Benzene) = 3\ C_6H_5(C_2H_5)\ (Ethylbenzene)$

MATERIAL AND ENERGY FLOWS FOR BENZENE ALKYLATION PROCESS

Table 4 summarises the material and energy flows for the benzene alkylation process. They are based on the Badger EBMax process described in [25], which matches closely with the process described above. The exothermic benzene alkylation process also produces steam of lower quality, which is assumed to be recovered and used in the PO/SM co-production process. Value ranges for the benzene and ethylene input are sourced from [26], where the input amount shall differ based on the purity of the input streams. Benzene and ethylene are purchased from steam cracking facilities within the region and are transported through ship and pipeline [27]. The HAS product, together with other waste fuels from the PO/SM co-production process, are exported as waste fuels to external parties.

Table 4: Material and energy flows for the benzene alkylation unit

Material/Energy	Unit	Value (range)	Reference
Input			
Benzene	t/t of EB	0.739 (0.735 - 0.746)	[25], [26]
Ethylene	t/t of EB	0.265 (0.254 - 0.265)	[25], [26]
High-Pressure Steam	GJ/t of EB	2.98	[25], using conversion factor of 3042MJ/ton[4]
Output			
Medium (MP)-to-Low-Pressure (LP) Steam	GJ/t of EB	3.8	[25], using conversion factor of 2743 MJ/ton[5]
Heavy Aromatic Solvents (HAS)	kg/t of EB	3 - 5.6	[26]

4.1.2. PROPYLENE OXIDE (PO)/ STYRENE MONOMER (SM) CO-PRODUCTION PROCESS

The PO/SM co-production process utilises the ethylbenzene produced in the Benzene Alkylation unit as the primary feedstock. Other raw input materials include propylene and hydrogen. The PO/SM can be further divided into seven main successive production units as shown in Figure 7. Unless stated otherwise, the process is further elaborated based on [13], of which detailed process description and process flow diagrams can be found.

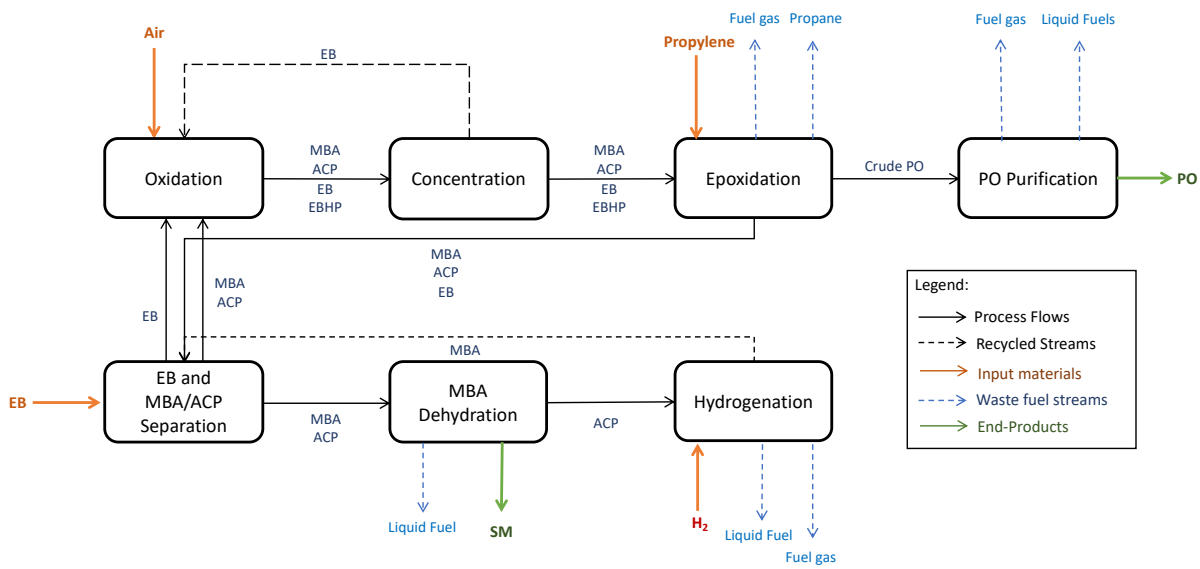

Figure 7: Process flow diagram of the PO/SM co-production (adapted from Figure 12 in [13]).

[4] This assumes that the steam is provided at a pressure level of 50 bar(g) and 340 °C [116]

[5] This assumes that the steam is provided at a saturated pressure level of 4.5 bar(g) [13]

Oxidation

Oxidation is the first chemical reaction step of the PO/SM process. Ethylbenzene (EB) is oxidised into ethylbenzene hydroperoxide (EBHP), methylbenzyl alcohol (MBA) and acetophenone (ACP). The input material, EB, is fed from the EB and MBA & ACP separation unit. The oxidation reaction takes place within two oxidation reactors that are connected in series, at an operating temperature of around 148°C and operating pressure of 2.4 to 2.7 bar(g). The air, which contains oxygen necessary for the reaction, is brought to the operating pressure with an electric compressor and fed into the reactors through spargers. The chemical reactions are as described using the reaction equations below:

Main exothermic reactions:

1) $C_8H_{10}\ (EB) + O_2 \Longrightarrow C_8H_{10}O_2\ (EHBP)$ $\Delta H = -101kJ/mol$
2) $C_8H_{10}\ (EB) + \frac{1}{2}O_2 \Longrightarrow C_8H_{10}O\ (MBA)$ $\Delta H = -190kJ/mol$
3) $C_8H_{10}\ (EB) + O_2 \Longrightarrow C_8H_8O\ (ACP)\ +\ H_2O$ $\Delta H = -390kJ/mol$

The final liquid product from the reactors is then fed to the concentration unit. On the other hand, the off-gas is cooled in the economiser where the residual EB is condensed, fractionated and recycled back to the oxidation reactors. The remaining non-condensable is scrubbed with a stream of MBA/ACP to recover EB, which the stream is then sent to the EB and MBA & ACP separation unit. A wastewater stream containing acids and peroxides are sent to a lye processing system.

Concentration

The objective of the concentration unit is to increase the EBHP content in the stream fed from the oxidation unit, from 8% to 35% by weight. The concentration process is conducted in two concentrators, which are connected in series and operated in a vacuum condition.

Epoxidation

The concentrated EBHP is reacted highly exothermically with propylene to form PO and ACP as the main products. At the same time, MBA and ACP are formed as the by-products, and later used in the styrene production unit. The epoxidation occurs in two epoxidation reactors that are connected in series, with operating temperature and pressure of around 93-110 °C and 41 bar(g), catalysed by molybdenum catalyst. The reactions are as follow:

1) $C_8H_{10}O_2\ (EBHP) + C_3H_6 \Longrightarrow C_3H_6O\ (PO)\ +\ C_8H_{10}O\ (MBA)$ $\Delta H = -209kJ/mol$
2) $C_8H_{10}O_2\ (EBHP) \Longrightarrow C_8H_{10}O\ (MBA)\ \ + \frac{1}{2}O_2$
3) $C_8H_{10}O_2\ (EBHP) \Longrightarrow C_8H_8O\ (ACP)\ \ + H_2O$

Following the epoxidation reaction in the reactors, the epoxidate stream is sent for distillation. The distillation process produces streams of fuel gas and propane-by products, which are exported or sold as fuel. This also produces a crude PO stream and a bottom product containing EB/MBA and ACP. Besides, a liquid stream is also produced and sent for the caustic water wash treatment.

PO Purification

The crude PO is then upgraded to saleble product of a purity of 99.9%, through a series of six extractive distillation columns. A few heat integration points are set up to utilise the recovered heat from the extractant circulatory system. Low-pressure steam is also utilised in three of the distillation columns, in

addition to the recovered heat. The distillation stage also produces a fuel gas stream and two liquid fuel streams.

EB and MBA/ACP Separation

The EB and MBA & ACP Separation unit is fed with three streams from the Epoxidation unit, Oxidation unit and the ACP Hydrogenation unit. The streams are subsequently distilled to separate the EB, higher hydrocarbons and other residues from the MBA/ACP stream. The EB is separated through vacuum distillation, sent for caustic treatment and eventually used as an input for the Oxidation unit, along with the fresh EB stream from the Benzene Alkylation unit. The final MBA/ACP stream is used as a feed for the MBA Dehydration and SM Purification unit. The separation process also produces salt-containing wastewater stream (referred internally as RFO-637) which is sent to AVR for incineration [27], as well as a glycolic fuel stream.

MBA Dehydration and SM Purification

The MBA in the final MBA/ACP stream fed from the EB and MBA/ACP separation unit is dehydrated to form styrene monomer (SM) in this unit. The MBA dehydration process is an endothermic reaction and takes place in the presence of a strong organic acid catalyst, the Para Toluene Sulfonic Acid (PTSA). The dehydrogenation takes place in two parallel reactors, at an operating temperature of 200 °C and pressure of 310 mbar(g). The main dehydration reaction and other side-reactions are as described by the chemical equations below:

1) $C_8H_{10}O\ (MBA) \Longrightarrow C_8H_8\ (Styrene)\ + H_2O \quad \Delta H = +146kJ/kg$
2) $C_8H_{10}O(MBA) \Longrightarrow C_8H_{10}(EB) + Heavies$
3) $2C_8H_8\ (SM) \Longrightarrow C_{16}H_{16}\ (styrene\ dimer)$

The vapour effluent is fed to a lye and water wash treatment and a series of distillation steps. This results in a pure stream of SM, a separated stream of MBA/ACP sent to the ACP Dehydrogenation unit, as well as liquid fuel.

ACP Hydrogenation

The hydrogenation of ACP into MBA occurs over fixed catalyst beds of copper oxide. The reactors are connected in series, with operating conditions ranging from 16 to 21 mbar(g) and 49 to 62 °C. It is also fed with an equal amount of EB from the storage tank and the required hydrogen is fed through a pipeline, supplied by an external party. Prior to the main hydrogenation process, the MBA/ ACP from the MBA Dehydration and SM Purification unit is first sent to a fractionator to separate out the heavy hydrocarbons through vacuum distillation, to prevent catalyst poisoning. The bottom product is then cooled and exported as fuel. The exothermic chemical reaction between ACP and hydrogen is as described by the chemical equation below:

$C_8H_8O\ (ACP) +\ H_2 \Longrightarrow C_8H_{10}O\ (MBA) \quad \Delta H = -50kJ/mol$

Other side reactions include:

1) $C_8H_8\ (SM)\ +\ H_2 \Longrightarrow C_8H_{10}\ (EB)$
2) $C_8H_8O\ (MBA)\ +\ 2H_2 \Longrightarrow C_8H_{10}\ (EB) + H_2O$

The hydrogenate from the reactors is then sent to a flash drum to remove the waste gas. The remaining hydrogenate is recycled to the EB and MBA/ACP Separation unit.

MATERIAL AND ENERGY FLOWS FOR THE PO/SM CO-PRODUCTION PROCESS

Table 5 summarises the energy and material flows for the PO/SM co-production process. The required ethylbenzene is produced on-site through the benzene alkylation process as described in 4.1.1. Propylene is sourced from steam cracking facilities and is transported through ship and pipeline [27], while hydrogen is sourced via pipeline from Air Liquide [28]. A number of waste fuel streams are identified, which the energy content is approximated based on indicative amount provided in [29] for the year 2006. The heavy liquid fuel output also includes the HAS stream from the benzene alkylation process. The glycolic fuel, heavy liquid fuel and vapour gas streams are sent to external utility company(ies) as replacement fuel, while propane stream is sold to regular fuel market [27]. On the other hand, the RFO-637 is sent to AVR Rozenburg as combustible fuel for the incineration of the caustic wastewater (CWW). The processes generally produce around 22kton of CWW per year [29].

Table 5: Material and energy flows for the PO/SM co-production process

Material/Energy	Unit	Value (range)	Reference
Input			
Ethylbenzene	t/t of SM	1.15 (1.1-1.2)	[26]
Propylene	t/t of SM	0.33	Approximated based on propylene: PO stoichiometric ratio of 1:1
Hydrogen	kg/t of SM	4.17	Approximated based on maximum annual required quantity indicated in [13]
Electricity	GJ/t of SM	0.6 (0.576 – 0.72)	[26]
Steam (net input)	GJ/t of SM	5.89	see footnote[6]
Output			
Glycolic Fuel	GJ/t of SM	0.57	[29]; conversion factor of 41 GJ/ton
Heavy Liquid Fuel	GJ/t of SM	1.43	[29]; conversion factor of 41 GJ/ton
Vapour Gas	GJ/t of SM	0.55	[29]; conversion factor of 45.2 GJ/ton
Propane	GJ/t of SM	0.42	[29]; conversion factor of 45.2 GJ/ton
Other Combustible Stream (RFO-637)	t/t of SM	0.03	[29]

4.1.3. ENERGY CONSUMPTION AND CO_2 EMISSIONS

ANNUAL ENERGY CONSUMPTION

Table 6 shows an estimation of the annual energy consumption for both the benzene alkylation and PO/SM co-production process. The figures are estimated based on the SM production capacity of 864 kton and the energy consumption values (on per unit tonne of product basis) indicated in Table 4 and Table 5.

[6] Net steam input for the PO/SM Co-production refers to net steam input from external utility company(ies). This assumes a gross steam input of 11.16 GJ/ton SM (value range between 11.16 and 14.04 GJ/ton of SM [25]), as well as utilisation of recovered heat from benzene alkylation process and PO/SM process, with an amount of 4.19 [25] and 1.08 [26] GJ/ ton of SM, respectively.

Table 6: Annual energy usage for the PO/SM co-production process

Steam (PJ/year)	Electricity (PJ/year)	Total (PJ/year)
7.9	0.5	8.4

SUPPLY OF UTILITIES

The main utilities required for the production of PO and SM through benzene alkylation and PO/SM co-production processes are electricity and high-to-medium pressure steam. These are exclusively sourced from the neighbouring utility sites, namely the Utility Centre Maasvlakte Leftbank (UCML) and Maasvlakte Power Plant 3 (MPP3). These two utility sites are owned by Uniper (formerly known as E.ON Benelux). An integrated steam system of four steam pressure levels[7] is established in the Maasvlakte site to enable cascaded use of steam. For example, the high pressure (HP) steam condensate from one process is connected to the medium pressure (MP) steam system for use in other processes [13]. The utility sites receive waste fuel streams, namely the glycolic fuel, fuel gas and heavy fuel from LyondellBasell's Maasvlakte site as replacement fuel [27–30]. Nevertheless, the exact proportion of the steam and electricity sourced from the two different sites, as well as the proportion of the fuel streams received by them, are not known from public sources. A short description of the two utility companies is included in Appendix A.1.

ANNUAL CO_2 EMISSIONS

Figure 8 shows the annual CO_2 emissions for the Maasvlakte production site. Scope 1 emissions refer to their reported emissions for the year 2019 [8]. As there is no known on-site steam boilers or furnaces from public sources, the scope 1 emissions could likely be attributed to the flaring, catalytic converter and thermal combustor systems [13]. The exact proportions of steam supply from UCML and MPP3, as well as their respective steam and electricity emission factors are not known. Therefore, the scope 2 emissions are quantified based on a gas-fired CHP electrical and steam thermal efficiency of 36% and 49%[8], respectively. This hence refers to electricity and steam emission factors of 85.4 and 52.8 kg/GJ, respectively, as determined based attribution method suggested in [31] (See Appendix A.4 for the attribution formula).

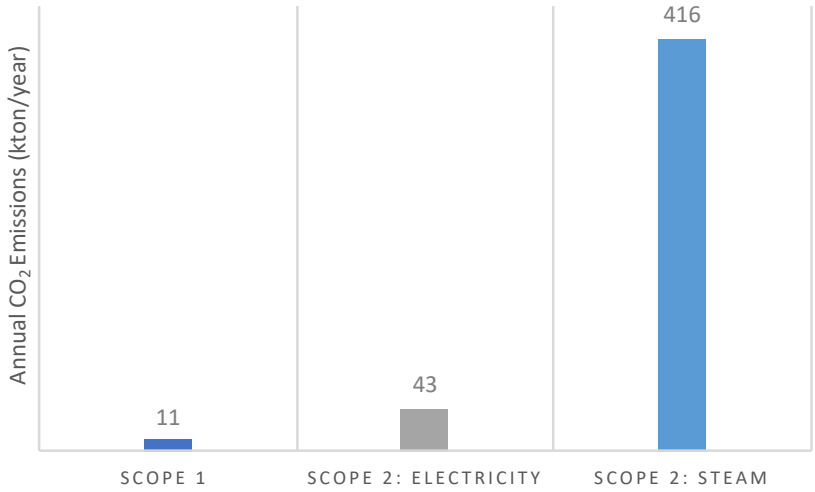

Figure 8: Estimated annual emissions for the Maasvlakte site

[7] The four steam pressure levels are HP (50 bar(g)), MP (20 bar(g)), LP (4.5 bar(g)), and LLP(2.5 bar(g).

[8] Based on reference efficiencies for 45MW_e GT in [132]

The gas-fired CHP with electrical and steam thermal efficiency of 36% and 49% is assumed as the reference technology, while the 416 kton of scope 2 steam-related emissions serve as the baseline emissions for the MAC curve analysis.

4.2. CURRENT PRODUCTION PROCESSES IN BOTLEK

LyondellBasell's Botlek production site produces a wide range of chemical products (see Table 3). The production facility started with the propylene oxide/tert butyl alcohol (PO/TBA) co-production process in 1972, and has since then expanded to incorporate five other main production processes. The history of expansion is described in 3.1.2. These other chemical processes utilise the PO and TBA as their input materials to subsequently produce saleable end products or input material for another process [22–29]. The material relationships of the different chemical processes at the Botlek production site are illustrated in Figure 9. To further explain, part of the PO produced from the PO/TBA process is utilised as input materials for other chemical processes on-site, producing proplyene glycol (PG), propylene glycol methyl ether (PGME), as well as in the Butanediol (BDO) process. The remaining PO is sold as final products to external parties. The TBA is either further purified and sold as gasoline grade TBA or further processed into isobutylene, the precursor chemical for the on-site production of methyl tertiary-butyl ether (MTBE) and ethyl tertiary butyl ether (ETBE). The co-product, tert butyl hydroperoxide (TBHP), is purified into saleable end-product at a much lower capacity of around 12kton annually [7].

The six main chemical processes to be described in this subchapter are as follows:

4.2.1. Propylene oxide/tert butyl alcohol (PO/TBA) co-production (also includes the isomerisation of n-butane)
4.2.2. Production of propylene glycol (PG)
4.2.3. Production of propylene glycol methyl ether (PGME)
4.2.4. Production of isobutylene
4.2.5. Production of methyl tertiary butyl ether (MTBE) and ethyl tertiary butyl ether (ETBE)
4.2.6. Production of 1,4-butanediol (1,4-BDO), allyl alcohol & methyl propanediol (MPD)

Associated with the PO/TBA process are the TBHP purification process and the TBA purification process. The TBHP purification process utilises part of the effluent stream from the PO/TBA process to produce a concentrated TBHP solution. The TBA purification process instead purifies the crude TBA into gasoline grade TBA. The processes adopted for the TBHP purification and TBA purification in LyondellBasell's operation is however not known, hence not further described in this report.

The material and energy flows for the individual processes are included in their respective subsections. Additionally, the overall annual energy consumption is estimated in 4.2.7. The estimated annual material consumption based on full production capacities and amount of waste fuel produced are summarised in Appendix A.2.

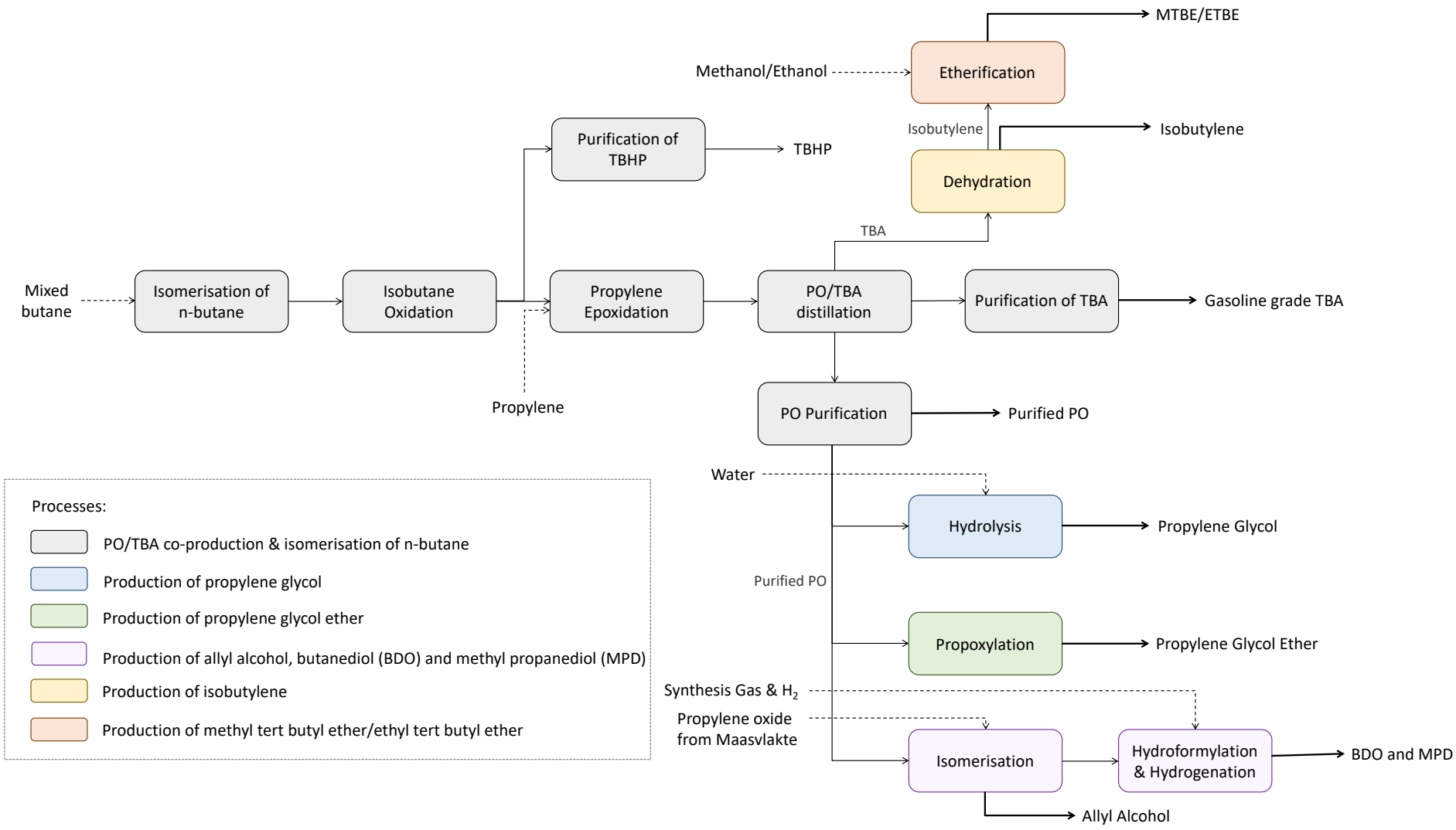

Figure 9: Material relationships of the different chemical processes at the Botlek production site (adapted from [29])

4.2.1. PROPYLENE OXIDE/TERT BUTYL ALCOHOL (PO/TBA) CO-PRODUCTION PROCESS

The co-production process produces PO and TBA as the main co-products, as well as tert butyl hydroperoxide (TBHP) as the by-product. The process utilises propylene and isobutane as the main raw input materials. The isobutane feedstock is obtained from LyondellBasell's on-site butane isomerisation facility, which isomerises mixed butane stream into isobutane [29]. The isomerisation process is further described in subsection 4.2.1.1.

The PO/TBA co-production process can be further differentiated into two main successive units, the Isobutane Oxidation unit and the Propylene Epoxidation unit. The processing units are schematically presented in Figure 10 and further described in the following paragraphs based on [32] unless stated otherwise. This process description is said to be reflecting LyondellBasell's conventional PO/TBA process in the United States [32].

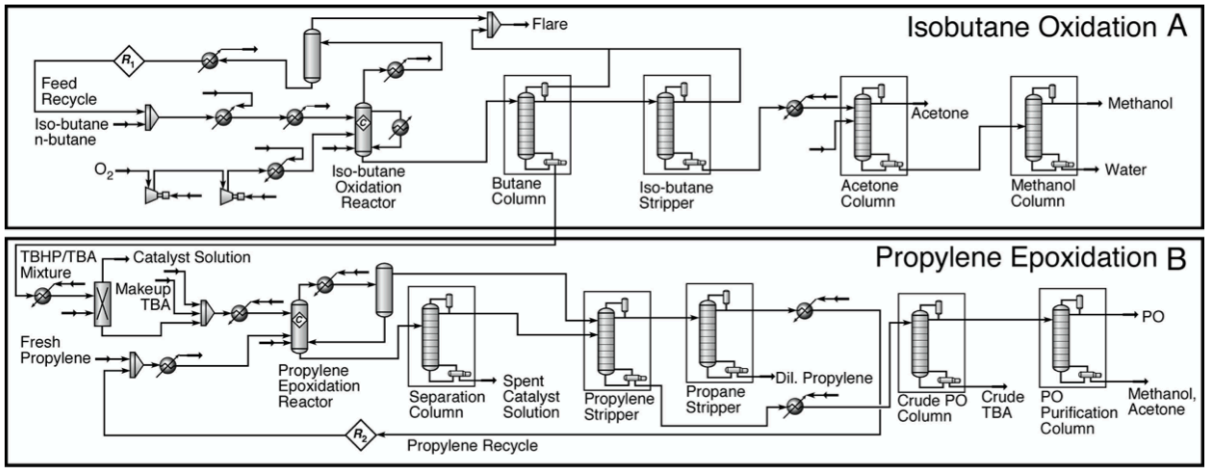

Figure 10: Process flow of the PO/TBA co-production process [32].

Isobutane Oxidation

This stage involves the exothermic oxidation reaction between isobutane and oxygen to form TBHP and the major co-product, TBA. The TBHP and the TBA will then be fed to the second unit, propylene epoxidation, of which TBHP will further react with propylene to form propylene oxide. The oxidation occurs in a non-catalytic liquid phase in six parallelly-arranged continuous stirred tank reactors (CSTR), with typical conditions of 3 MPa and 135 °C. The reaction has an average residence time of 10 hours. The oxygen concentration in the liquid is kept below 4-7 mol%. The chemical reactions forming TBHP and TBA can be described with the chemical equations below [33]:

1) $C_4H_{10}\ (Isobutane)\ +\ O_2 \Longrightarrow C_4H_{10}O_2\ (TBHP)$ $\qquad \Delta H = -251.5\ kJ/mol$

2) $C_4H_{10}(Isobutane)\ +\ \frac{1}{2}\ O_2 \Longrightarrow C_4H_{10}O\ (TBA)$ $\qquad \Delta H = -208.5\ kJ/mol$

The exothermic reaction also vaporises part of the mixture, which is partially condensed to recover the isobutane back to the reactors. The liquid fraction of the reactors, containing both unreacted reactants and products, are sent to a series of distillation columns where TBA and TBHP are recovered from other by-products. Cooling water is used in the condensers in all the distillation columns.

Propylene Epoxidation

TBHP formed in the Isobutane Oxidation unit is reacted with propylene in four parallelly-arranged stirred tank reactors to form propylene oxide and TBA. The epoxidation reaction occurs over a residence time of 2 hours, with operating conditions of 3.5 MPa and 121 °C, in the presence of a homogeneous molybdenum-based catalyst. The exothermic epoxidation reaction can be described using the chemical equation below [33]:

$$C_3H_6\ (Propylene)\ +\ C_4H_{10}O_2\ (TBHP)\ \Longrightarrow C_3H_6O\ (PO)\ +\ C_4H_{10}O\ (TBA)$$

Following the epoxidation reaction, the liquid effluent is sent to a series of distillation column where PO and crude TBA are separated out from the remaining mixture. The distillation stages also allow the catalyst solution and unreacted propylene to be recovered, while crude PO is further purified in the presence of octane as an extractive agent [29–34].Referring to Figure 10, the Separation Column, Propane Stripper and PO Purification Column are chilled with normal cooling water, while Propylene Stripper and Crude PO Column are cooled with chilled water.

4.2.1.1. ISOMERISATION OF N-BUTANE

The butane isomerisation process serves to isomerise straight-chain n-butane into isobutane. The isobutane is then used as the input material for the PO/TBA co-production process. As indicated in [35], LyondellBasell has an isomerisation capacity of 80 tonnes per hour. There are several different process configurations, differing in ways such as the type of catalyst utilised (i.e. zeolite or chloride-promoted), reaction temperatures, separator equipment used (i.e. separation based on boiling points or molecular size). These variations can be found described in [36–39]. Nonetheless, the exact process configuration utilised in the Botlek site is not known.

In general, the mixed-butane feedstock is first dried and then fed to the isomerisation reactors. The operating conditions differ depending on the type of catalyst used. Hydrogen gas is also added to inhibit the formation of olefins/carbon deposits [38–39]. Following the isomerisation process, the light ends are fractionated and exported as fuel gas or sent to a recovery unit. Depending on the process configuration, the remaining stream, which contains unconverted n-butane, may or may not be sent to an additional separation column to recycle the unreacted n-butane [38]. The recycling of unconverted n-butane shall lead to a yield between 95-98%, or otherwise, an 80% conversion rate [38].

MATERIAL AND ENERGY FLOWS FOR PO/TBA CO-PRODUCTION PROCESS

This section elaborates on the energy and material flows for the PO/TBA co-production process, as well as the n-butane isomerisation process, as shown in Table 7 and Table 8. The isobutane feedstock is provided by the on-site butane isomerisation capacity, which utilises mixed butane stream obtained from an external party [35]. The propylene feedstock is supplied from steam cracking installations through ship and pipeline [27], while the oxygen is supplied by Air Products.

As noted in the butane isomerisation process description above, the exact process configuration used by LyondellBasell is not known. A wide range of utility requirements is provided for the isomerisation of C4-C6 feedstock in [38], covering a spectrum of possible process configurations. The utility requirements shall differ based on the catalyst technology used, the separation method and the recycling process(es) involved. The mixed butane feed input is calculated based on an assumed yield of 95%. The annual mixed butane

feedstock (see Table 36) is calculated assuming all isobutane required for the PO/TBA process is provided by the isomerisation unit [35].

Table 7: Material and energy flows of the PO/TBA process

Material/Energy	Unit	Value	Reference
Input			
Isobutane	t/t of PO	1.94	Approximated based on isobutane conversion efficiency of 100%, TBHP molar selectivity (based on isobutane consumption) of 53.4% and TBHP conversion rate of 98% and PO molar selectivity (based on TBHP consumption) of 98.5% [32]
Propylene	t/t of PO	0.72	Approximated based on conversion efficiency and molar selectivity of 100%, and propylene: PO stochiometric ratio of 1:1 [32]
Oxygen	t/t of PO	0.79	Approximated based on TBHP:O_2 and TBA:O_2 stochiometric ratio of 1:1 and 1:0.5
Electricity	GJ/t of PO	2.77	[32]
Steam	GJ/t of PO	17.58	Approximated based on steam input parameter provided in [32][9] and conversion factor of 3042 MJ/ton[10]

Table 8: Material and energy flows of the butane isomerisation process

Material/Energy	Unit	Value (range)	Reference
Input			
Mixed butane	t/t of isobutane	1.05	Approximated based on assumed yield of 95% [38]
Electricity	GJ/t of isobutane	0.09 (0.07-0.108)	[38]
Steam	GJ/t of isobutane	1.37 (0.91-1.83)	Approximated based on steam input parameter provided in [38][11] and conversion factor of 3042 MJ/ton[10]

4.2.2. PRODUCTION OF PROPYLENE GLYCOL (PG)

The production of propylene glycol (PG) utilises the propylene oxide (PO) produced on-site through the PO/TBA co-production process, as the main input material. PG is produced through the direct hydrolysis of PO with water. The process flow is schematically represented in Figure 11, consisting of the hydrolysis reactors, dehydration columns and distillation columns. The process is further described in the following paragraphs, primarily based on [40] unless stated otherwise.

[9] Steam input of 5.78 t/t of PO [32]
[10] This assumes that the steam is provided at a pressure level of 50 bar(g) and 340 °C [116]
[11] Steam input range of 0.3 – 0.6 t/t of isobutane [38]

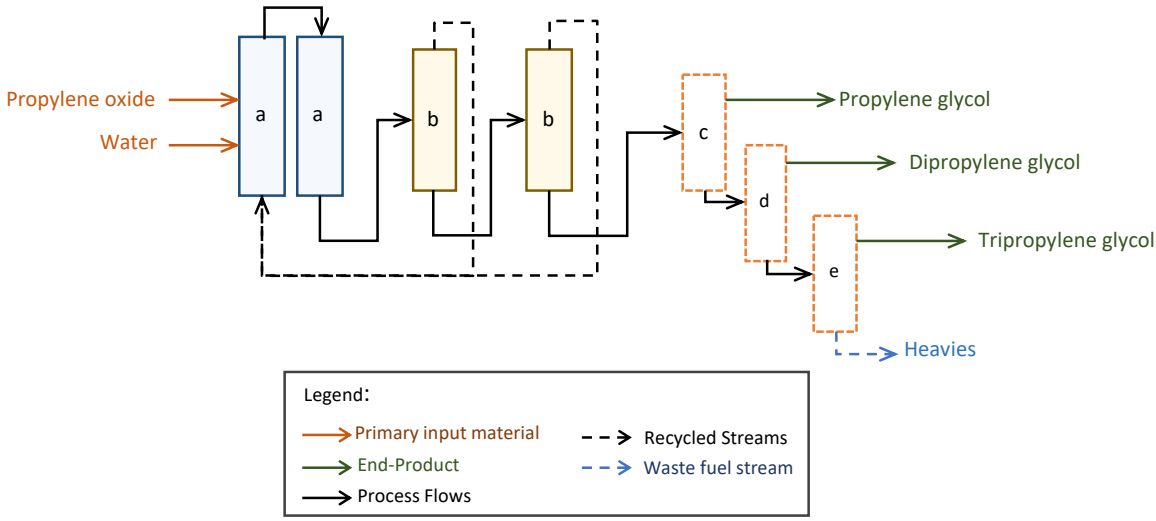

Figure 11: Process flow diagram in producing PG through the hydrolysis of PO. a) Hydrolysis reactors; b) Dehydration columns; c – e) Vacuum distillation columns (as adapted from [40])

PO and water are fed into the two serially-arranged reactors at a molar ratio of 1:15, where the hydrolysis occurs without the presence of a catalyst. The excessive amount of water limits the formation of dipropylene glycol (DPG) and tripropylene glycol (TPG) [41]. The initial operating conditions are at 125 °C and approximately 2 MPa, of which the reactor temperature rises to 190 °C due to the exothermic reaction. The hydrolysis reaction can be described with chemical equations below:

Main reaction [42]:

$$C_3H_6O\ (PO)\ +\ H_2O\ \Longrightarrow C_3H_8O_2\ (PG) \qquad \Delta H = -351\ kJ/mol$$

The reaction effluent generally consists of PG, DPG and TPG in the ratio of 100:10:1 [40], which shall vary depending on the propylene oxide to water ratio. Following the reaction, the liquid effluent is first fed to dehydration columns. Water is stripped off from the effluent and is recycled back to the reactors. The remaining stream is fed to a series of vacuum distillation columns, where PG, DPG and TPG are separated from each other. The heavy residues, consisting of heavier glycols, can be used as fuel [41].

MATERIAL AND ENERGY FLOWS FOR PG PRODUCTION

Table 9 summarises the material and energy flows for the production of PG, on per unit tonne of PG basis, as sourced from [43]. The numbers provided in the literature are as modelled by the authors using Aspen Plus with Peng-Robin thermodynamic property method. 90% of the steam consumption is consumed by the distillation columns.

Table 9: Material and energy flows for the production of PG

Material/Energy	Unit	Value (range)	Reference
Input			
Propylene Oxide (PO)	t/t of PG	1.10	[43], which assumed conversion rate to PG of 89%
Electricity	GJ/t of PG	0.11	[43]
Steam	GJ/t of PG	9.28	Approximated based on primary fuel input in [43] using boiler efficiency of 80%[12]

[12] As assumed in [43].

4.2.3. PRODUCTION OF PROPYLENE GLYCOL METHYL ETHER (PGME)

Propylene glycol methyl ether (PGME) is synthesised through the propoxylation reaction between methanol and propylene oxide (PO) [29–44]. The PO is manufactured on-site through the PO/TBA process. The reaction occurs in a closed system, at operating conditions of 94 to 180 °C and 26 bar [45]. Various types of acid and alkali-based catalysts can be used [46]. The reaction is exothermic with the heat of reaction ranging between -80 to -100 kJ/ mol [47]. The reaction also produces by-products including dipropylene glycol methyl ether (DPGME), tripropylene glycol methyl ether (TPGME), and other heavier ethers [46–47]. It is noted that 2-methoxy-1-propanol will also form, which can be recovered and converted into PGME [45]. The main reaction is described with the chemical equation as follows:

$$C_3H_6O\ (PO)\ +\ CH_3OH\ \Longrightarrow C_4H_{10}O_2\ (PGME)$$

The reactor effluent is then fed to a series of distillation columns. The excess methanol is recovered and recycled to the reactor from the first column. The remaining effluent is then further distilled into different ether streams [45–47]. The bottom product, containing the catalyst solution, is recycled and reused or incinerated [26–45].

MATERIAL AND ENERGY FLOWS FOR PGME PRODUCTION

Table 10 summarises the material and energy flows for the production of PGME, on per unit tonne of PGME basis. The energy inputs are as approximated in [48] for the production of ethylene glycol methyl ether (EGME), based on a large chemical production plant in Germany. The EGME is formed from the reaction between ethylene oxide and ethanol. Nevertheless, it is assumed that the energy input values are applicable for the production of PGME, as the two processes shares a similar process flow and differ from each other within a relatively narrow range of operating conditions [47].

Table 10: Material and energy flows for the production of PGME

Material/Energy	Unit	Value	Reference
Input			
Propylene Oxide (PO)	t/t of PGME	0.76	approximated based on conversion efficiency of 100% and molar selectivity of 85% [47]
Methanol	t/t of PGME	0.42	approximated based on PGME:methanol stoichiometric ratio of 1:1, conversion efficiency of 100% and molar selectivity of 85%
Electricity	GJ/t of PGME	1.2	[48]
Steam	GJ/t of PGME	1.6	approximated from primary fuel input provided in [48] with assumed natural gas boiler efficiency of 80%

4.2.4. PRODUCTION OF ISOBUTYLENE

The production of isobutylene at LyondellBasell's Botlek site is through the dehydration process of tert butyl alcohol (TBA). The TBA is formed from the PO/TBA co-production process, as described in 4.2.1. The produced isobutylene is then used as the inputmaterial to produce methyl tertiary-butyl ether (MTBE) and ethyl tertiary butyl ether (ETBE) through etherification process (as described in 4.2.5) or sold as a final product.

The dehydration process can be carried out in the liquid or vapour phase (with a temperature between 260 and 370 °C), while the latter requires higher-cost equipment and more energy. In addition, different types of catalyst and an azeotroping agent may be used, depending on the process design [49–50]. The process described below is a liquid phase dehydration reaction, based on a European patent assigned to ARCO Chemical Technology, L.P. (currently known as LyondellBasell) [50] unless stated otherwise.

The TBA is dehydrated into isobutylene and water endothermically, in the presence of para toluene sulfonic acid (PTSA) catalyst. The dehydrator is operated at a temperature of 160 °C and pressure of approximately 14 bar [51]. The reversible reaction can be described with the chemical equation [52] as follows:

$$C_4H_{10}O\ (TBA)\ \rightleftharpoons\ C_4H_8\ (Isobutylene)\ +\ H_2O \qquad \Delta H =\ 26 - 34\ kJ/mol$$

Following that, the stream is sent to the separation zone for further phase separation. The cooled reaction mixture consists of three phases, a vapour stream, an organic-rich layer and a water-rich layer. The vapour stream, made up of 96.4% of isobutylene, is separated from the liquid condensate as the final product. The organic-rich condensate is recycled back to the dehydrator, while the water-rich layer is removed as a wastewater stream.

MATERIAL AND ENERGY FLOWS FOR ISOBUTYLENE PRODUCTION

Table 11 summarises the material and energy flows for the production of isobutylene, on per unit tonne of isobutylene basis. The energy consumption data is sourced from [53]. The process assessed in [53] has however assumed the use of a zeolite based catalyst with phosphoric acid, instead of a PTSA catalyst.

Table 11: Material and energy flows for the production of isobutylene

Material/Energy	Unit	Value (range)	Reference
Input			
Tert butyl alcohol (TBA)	t/t of isobutylene	1.43	Approximated with conversion efficiency of 98% and stream purity of 94.5% [50]
Electricity	GJ/t of isobutylene	0.22	[53]
Steam	GJ/t of isobutylene	14.21	[53]; equivalent to 5.1 ton of steam at 13.79 bar

4.2.5. PRODUCTION OF METHYL TERTIARY BUTYL ETHER (MTBE) AND ETHYL TERTIARY BUTYL ETHER (ETBE)

LyondellBasell's Botlek site has a total annual production capacity of 400 kton for both methyl tertiary butyl ether (MTBE) and ethyl tertiary butyl ether (ETBE), though the proportions of the two products are not known [23]. The production processes of MTBE and ETBE are similar in terms of the reaction process [49–54] and only require slight configuration modifications [38], as further explained below. MTBE is produced through the etherification process between isobutylene and methanol, while ETBE forms from the reaction between isobutylene and ethanol.

Part of the required isobutylene is sourced from the on-site isobutylene production unit (as described in 4.2.4), which has an annual capacity of 100 kton. The remaining input is expected to be supplemented by external party. The methanol and ethanol are sourced from external parties. In addition, bio-based ethanol is also used to produce bio-ETBE, of which the capacity is not known [55]. The etherification process

described below is generally applicable for the MTBE production process, primarily based on [26] unless stated otherwise.

MTBE production

The process configuration may either involve two reactors in a so-called conventional process (Figure 12) or combination of a reactor and a reactive distillation column in a so-called reactive distillation process (Figure 13), prior to further distillation. In both process configurations, the etherification reaction between methanol and isobutylene is catalysed using an acidic ion exchange resin catalyst and operated under the pressure of 14 bar(g) and a temperature range of 45-90 °C [25–38]. The etherification reaction can be described with the chemical equation [56] below:

$$C_4H_8\ (Isobutylene)\ +\ CH_3OH\ (methanol)\ \rightleftharpoons\ C_5H_{12}O\ \ (MTBE) \qquad \Delta H\ =\ -37.3\ kJ/mol$$

The effluent is then fed into either a reactive distillation column or a second reactor, allowing a second-time reaction to take place, maximising the conversion rate to over 99%. In the process where reactive distillation column is used, the ether stream is recovered as the bottom product from the reactive distillation column. Whereas in the conventional process, the effluent is fed to the debutaniser for MTBE recovery. Subsequently, the effluent from either the distillation column or the debutaniser is fed to a water wash column where methanol readily dissolves in the water solvent and the raffinate is removed. The resulting methanol-water mixture is then distilled, and the recovered methanol stream is recycled back to the first reactor. The use of pervaporation membrane as a separation method is also noted in [49].

The process employed at LyondellBasell's Botlek site is likely to be a conventional process, where adiabatic fixed bed reactors are used [57]. It is also mentioned in [58], that the reaction occurs in the presence of a sulfonic acid catalyst, under operating conditions of 50 °C and 14 bar.

ETBE production

It is noted in [38] that the MTBE unit may be used to produce ETBE with minor modifications. The modifications include increasing the bottom temperature in the catalytic column, adjusting the temperatures in ethanol/water column and increasing the capacity of the column and cooler.

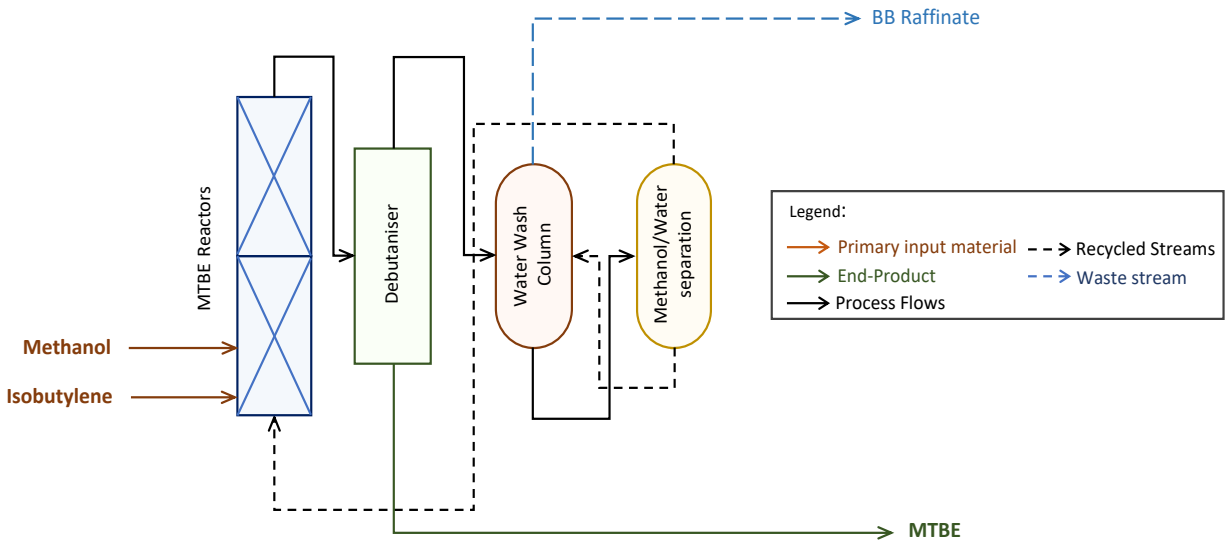

Figure 12: A simplified process flow diagram, adapted from an Uhde (Edeleanu) MTBE process utilising two serially connected reactors shown in [25].

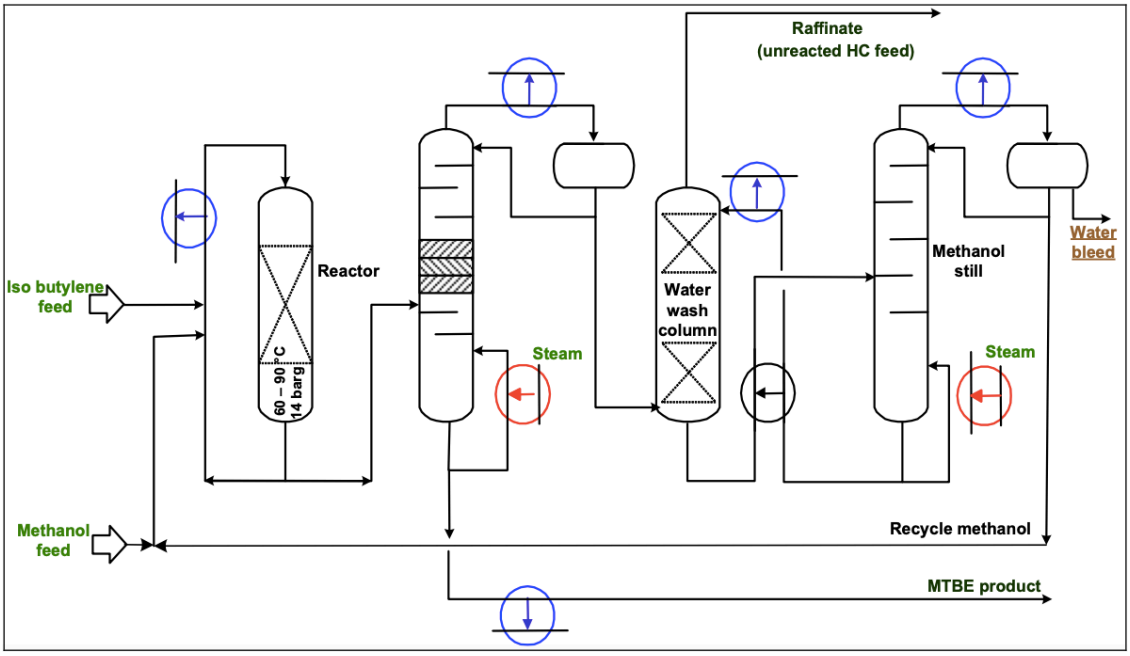

Figure 13: Process flow diagram of a simplified MTBE plant utilising reactive distillation column. This figure is sourced directly from [38] (Figure 2.16).

MATERIAL AND ENERGY FLOWS FOR THE ETBE/MTBE PRODUCTION

Table 12 summarises the material and energy flows for the production of MTBE/ETBE, on per unit tonne of product basis. The ETBE process is likely to require a higher amount of processing heat content than a MTBE process.

Table 12: Material and energy flows for the production of MTBE/ETBE

Material/Energy	Unit	Value (range)	Reference
Input			
Isobutylene	t/t of MTBE	0.65	approximated with conversion efficiency of 99% [38] and molar selectivity of 99.5% [25]
Methanol	t/t of MTBE	0.36	approximated based on MTBE: methanol stoichiometric ratio of 1:1
Isobutylene	t/t of ETBE	0.45	approximated with conversion efficiency of 99% [38] and molar selectivity of 99.5% [25]
Ethanol	t/t of ETBE	0.56	approximated based on ETBE: ethanol stoichiometric ratio of 1:1
Electricity	GJ/t of MTBE	0.06 (0.04-0.07)	[38]
Steam	GJ/t of MTBE	4.3 (2.9-5.7)	Approximated based on steam input parameter provided in [38] [13] and conversion factor of 2863 MJ/ton[14]

[13] Equivalent to 1.5 ton (range between 1-2 ton) of steam input per tonne of MTBE [38]

[14] assumes that the steam is provided at a pressure level of 20 bar(g) and 235 °C [116]

4.2.6. PRODUCTION OF 1,4-BUTANEDIOL (BDO), ALLYL ALCOHOL & METHYL PROPANEDIOL (MPD)

The production of 1,4-Butanediol (BDO) utilises the propylene oxide (PO) produced on-site or from the Maasvlakte site [22], in addition to other input materials such as syngas and hydrogen supplied by Air Products. The BDO production also yields saleable by-products such as allyl alcohol and methyl propanediol (MPD, an isomer of BDO). While several alternative routes are available in producing the different products, the BDO production route from PO, which together yields allyl alcohol and MPD, provides the highest economic feasibility by utilising self-produced PO as raw material [59]. The production technology is originally developed by a Japanese chemical manufacturer, Kuraray [60].

The BDO production involves two main units, namely the allyl alcohol unit and the BDO unit. The overall BDO yield is at around 77 mol% of propylene oxide [61]. The process flow is as illustrated in Figure 14 and described in the following paragraphs. The process description is based primarily on [59] unless stated otherwise.

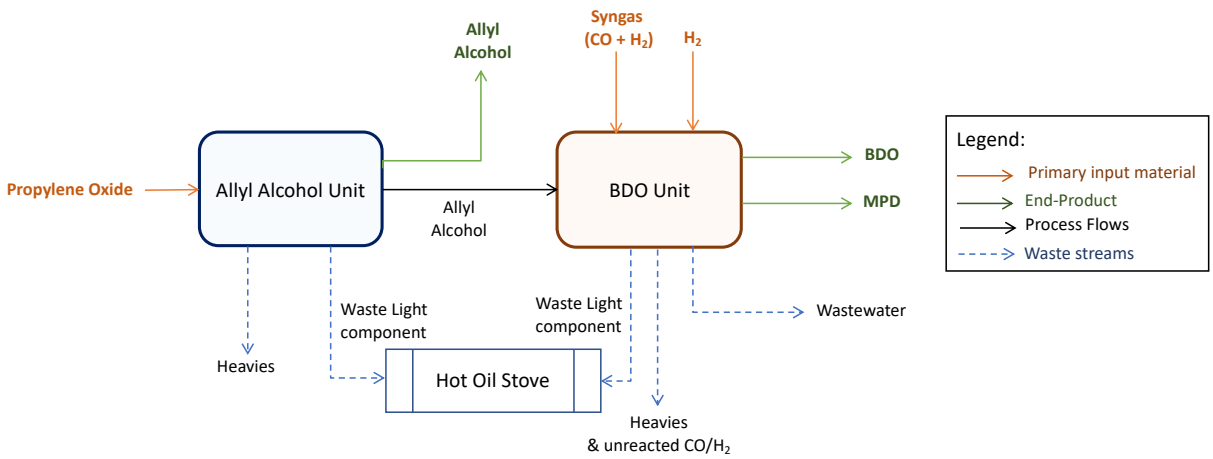

Figure 14: Process flow diagram of the production of BDO, allyl alcohol & MPD [59].

Allyl alcohol unit

PO is isomerised into allyl alcohol in this unit, in the presence of hot oil/metallic catalyst slurry. The slurry phase (alternatively a gas-phase) reaction is performed under the temperature of 300 °C and pressure of 1 bar [61]. The isomerisation process can be described with the chemical equation as follows:

$$CH_3CHCH_2O\ (PO) \Longrightarrow CH_2 = CHCH_2OH\ (Allyl\ Alcohol)$$

The reactor effluent is then fed to a multistage distillation zone. The unreacted PO stream is recycled back to the reactor and the lighter fraction is removed and used as waste fuel in the on-site hot oil stove. The final product, allyl alcohol is distilled out from the remaining stream. Additionally, the catalyst, of which the active surface may be contaminated with heavy by-products, is constantly regenerated. Acetone and thermal oil are distilled out and reused in the catalyst regeneration process. The remaining stream, containing heavy substances and contaminated catalyst is removed and exported to third parties as fuel.

Butanediol (BDO) unit

The allyl alcohol formed in the allyl alcohol unit is further converted into BDO through two chemical reactions, hydroformylation and hydrogenation. The allyl alcohol is first fed into the hydroformylation reactor, which

in reaction with synthesis gas (carbon monoxide (CO)/hydrogen (H_2) mixture) forms hydroxy-butyraldehyde (HBA). The reaction is likely to take place in the presence of a Rhodium-based catalyst dissolved in toluene solvent, with operating conditions of 3 bar and 60 °C [61]. Alternatively, other types of catalyst, temperature and pressure ranges between 20-100°C and 1.4-41 bar may be used [62]. The reaction effluent is later sent to the extraction zone, with water acting as the extractive agent. The toluene/catalyst mixture is recycled back to the reactor, while the remaining product-containing aqueous solution is fed to the hydrogenation reactor, after being stripped off of carbon monoxide. The hydroformylation reaction is as described with the chemical equation below:

$$CH_2 = CHCH_2OH\ (Allyl\ Alcohol)\ +\ CO + H_2\ \Longrightarrow C_4H_8O_2\ (HBA)$$

Following the extraction, the aqueous solution, containing HBA, is fed to the hydrogenation reactor. The reaction between HBA and hydrogen forms BDO, as well as MPD as a by-product. The hydrogenation is likely to occur over a reaction temperature of 150 °C and pressure of 35 bar, in the presence of Raney Nickel catalyst [61]. Alternatively, other types of catalyst, temperature and pressure ranges between 60-200 °C and 14-103 bar may be used [62]. Following the reaction, the catalyst is then removed from the reaction effluent by passing through a filter and an ion exchanger. The main hydrogenation reaction is as described with the chemical equation below:

$$C_4H_8O_2\ (HBA)\ + H_2\ \Longrightarrow\ C_4H_{10}O_2\ (BDO\ or\ MPD)$$

The remaining effluent, containing BDO and MPD, is then sent for further distillation, where purified streams of BDO and MPD are obtained. The remaining distillation fractions include a fraction of light component compounds, recovered as fuel for the on-site hot oil stove. In addition, heavies and unreacted CO and H_2 are removed and exported as waste fuel to external parties and the wastewater stream is sent for biological wastewater treatment.

MATERIAL FLOWS FOR THE BDO, ALLYL ALCOHOL & MPD PRODUCTION

Table 13 summarises the material flows for the production process, on per unit tonne of BDO or MPD basis. Regrettably, there is no public information on the electricity and steam consumption.

Table 13: Material flows for the BDO process

Material/Energy	Unit	Value (range)	Reference
Input			
Propylene Oxide (PO)	t/t of BDO	0.84	approximated with conversion yield of 77 mol% of PO [61]
Carbon Monoxide (CO)	t/t of BDO or MPD	0.31	approximated based on CO:BDO stoichiometric ratio of 1:1
Hydrogen (H_2)	t/t of BDO or MPD	0.04	approximated based on H_2:BDO stoichiometric ratio of 2:1

4.2.7. ENERGY CONSUMPTION AND CO_2 EMISSIONS

ANNUAL ENERGY CONSUMPTION

Figure 27 in Appendix A.2 shows an estimation of the annual energy usage for the different processes at the Botlek production site. The figures are estimated based on the production capacities listed in Table 3 and the energy consumption values (on per unit tonne of product basis) indicated in their respective material

and energy flows tables. Processes such as BDO production, TBHP purification and TBA purification are excluded as the information is not available.

Nevertheless, these figures shall be an overestimation of the overall energy consumption as it is expected that there is an efficient, cascaded use of steam throughout the production complex. To get a better indication of the overall steam usage, the EU-ETS free carbon certificate allocation of 506 kton [63], for the year 2013, is used as a reference estimation for the steam consumption. This corresponds to an 8.04 PJ of steam (or other measurable heat) consumption[15]. Without further verification from LyondellBasell, it is here assumed that the 2013 allocation reflects more or less the actual steam usage for the production site, as a whole. Notwithstanding, the expansion of isobutane isomerisation capacity in 2015 may have increased the total steam consumption slightly but is negligible (~2%).

Table 14: Estimated steam and electricity consumption for the Botlek Site

Steam (PJ/year)	Electricity (PJ/year)	Total (PJ/year)
8.0	0.9 [16]	8.9

SUPPLY OF UTILITIES

LyondellBasell's Botlek site has recently in 2016, started operating two on-site steam boilers with 115 MW_{th} capacity [64], fuelled mainly by natural gas and other waste gases, with a small fraction by liquid waste fuels. Additionally, it is noted that hot oil stoves are used on-site, utilising waste thermal oil as input [59]. LyondellBasell also obtains its electricity and steam needs from external utility sites, namely WKC Air Products and Eurogen C.V. Rotterdam Rozenburg. A short description of the utility companies is included in Appendix A.2.

LyondellBasell's steam supply is currently provided jointly by its own steam generation and external supply, as suggested by its scope 1 emissions. Nevertheless, it is assumed that the production site is capable of being self-sufficient, following the installation of the two steam boilers. The generally high scope 1 emissions prior to year 2016 suggested the presence of existing boilers (i.e. hot oil stoves [59]) for on-site steam generation, corresponding to around 1.5 PJ[17] of steam output. In addition to this, the new boilers shall allow a total steam production of 7 PJ, running at a 97% load. Hence, it can be concluded that the pre-2015 boilers (i.e. hot oil stoves) and new boilers would in theory capable to cover all of the steam requirements. Both the Eurogen C.V. Rotterdam Rozenburg and WKC Air Products have been in operations since 1994 and 2002 [65–66]. Given the retirement of the two utility sites are soon approaching, transitioning into being self-sufficient can be viewed as a logical choice. These assumptions have, however, not been verified by LyondellBasell.

[15] The free carbon certificate allocation is determined based on the "heat benchmarking", which assumes that the steam is provided by a natural gas boiler of 90% conversion efficiency, while also considering historical consumption and correction factors [133]. The heat (i.e. steam) usage is back-calculated using simplistic assumption that the free allocation reflects directly the actual steam usage, with no correction factors applied, as such: $\frac{506\ kton\ CO2}{56.6\ kton\ CO2/PJ} * 90\%$. 506 kton CO_2 corresponds to the carbon certification allocation, 56.6 kton CO_2/PJ corresponds to the emission factor of natural gas, and 90% is the assumed conversion efficiency of a natural gas boiler.

[16] Excluding the BDO production, TBHP purification and TBA purification processes

[17] Estimated based on estimated amount of fuel burnt on-site (see Table 37) and conversion efficiency of 79.5% (average between steam boiler efficiencies for fuel oil and waste gas)

The reference situation for the MAC analysis assumes a self-sufficient scenario, where the steam is generated on-site using existing facilities, using waste streams (estimated amount is shown in Table 37) and natural gas as fuel input.

ANNUAL CO_2 EMISSIONS

The reported Scope 1 emissions for the year 2019 is 322 kton [8], attributable to its on-site steam generation and other operations such as flaring, which is assumed negligible. The remaining steam-related emissions falls within the scope 2 emissions, with steam being supplied from external utility companies. However, there is no public data on the amount of steam supplied by external utility sites, hence the scope 2 emissions are not quantified. Alternatively, the annual steam-related emissions are estimated based on the self-sufficient scenario, which is proposed as the MAC reference situation. The detailed calculations are explained in Appendix A.2.

The scope 2 electricity emissions[16] are quantified based on a gas-fired CHP with electrical and steam thermal efficiency of 36% and 49%, respectively. The electricity emission factor is 85.4 kg/GJ, determined based attribution method suggested in [31] (See Appendix A.4 for the attribution formula).

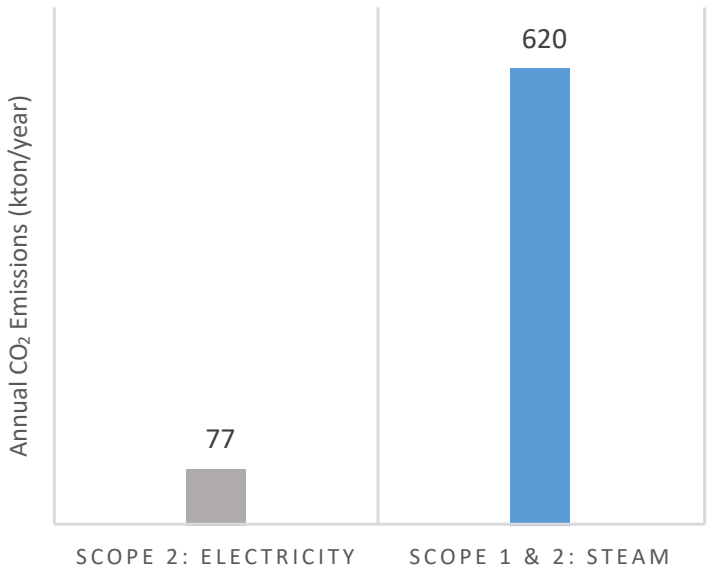

Figure 15: Estimated annual emissions from the Botlek site

CHAPTER 5: DECARBONISATION OPTIONS

The analysis performed on LyondellBasell's current operations at the Maasvlakte and Botlek production sites has indicated that the annual energy consumption is significant. The energy consumption is also the major contributor to LyondellBasell's carbon emissions (on scope 1 and 2 basis). Around 90% (for Botlek site) and 94% (for Maasvlakte site) of the consumed energy are for heating purposes, supplied in the form of processing steam. The remaining can be attributed to their electricity consumption.

This chapter proposes and discusses a number of decarbonisation options that are applicable for decarbonising LyondellBasell's operations at the two production sites. The decarbonisation focus is on the steam usage. The scoping decision is made on the basis that steam-related emissions constitutes at least 88% of LyondellBasell's total scope 1 and 2 emissions. Decarbonisation effort has largely been focused on the power sector, and the emissions resulted from electricity production is likely to decrease substantially over the years, with increasing renewable energy penetration. On the other hand, the decarbonisation of high-pressure steam remains a challenging endeavour.

A few constraints have been applied while shortlisting the most-promising decarbonisation options for the MAC curve analysis. Firstly, alternative processes in producing the same chemical products, which require a whole-process replacement and alternative feedstock, are not considered. The two production sites have been optimised in terms of their product flows, of which the end-product of one process is cascaded down to the next. Secondly, the decarbonisation options shall be drop-in options and not requiring modifications to the process configurations. This has hence excluded the possible process-specific energy efficiency measures and the options for further process heat integration. The reason for such constraint is due to the lack of fine technical details with regard to the broad range of chemical processes and their interdependencies (i.e. cascaded residual heat use). This poses difficulties to provide meaningful suggestions and quantitative analysis for such measures.

For the reasons mentioned above, the decarbonisation focus is further narrowed down to the decarbonisation of steam supply. Integrated steam systems are utilised in LyondellBasell operations, allowing a cascaded use of steam of different qualities across processing units. Decarbonisation of the steam supply would hence decarbonise the production sites, as a whole. The steam input is fed at high (50 bar(g)) and medium pressure (20 bar(g)) from external utility companies to the Maasvlakte site, while steam is both produced on-site and sourced from external parties for the Botlek site. In light of the generally high pressure and high temperature steam (>235°C) usage, the proposed decarbonisation options shall be able to fulfil such temperature and pressure needs. Lastly, the selected decarbonisation options shall be commercially mature by 2030. The decarbonisation options selected for the MAC curve analysis are as shown in Table 15.

The different options are described in their respective subchapters, detailing their technological concepts and application, as well as applicable technical and economic parameters (investment cost, operation & maintenance costs etc.). The technical and economic parameters are based on public sources, prioritising data most relevant for the Netherlands and reflect the possible technical and economic advancements for the year 2030.

Table 15: Selection of decarbonisation options for high-temperature steam

Category	Technology
Electrification	Electrode Boiler
Hydrogen (H_2) Combustion	H_2 Boiler + Off-site Blue H_2
	H_2 Boiler + Off-site Green H_2
	H_2 Boiler + On-Site Polymer Electrolyte Membrane (PEM)
	H_2 Boiler + On-site Alkaline Electrolysis (AEL)
Biomass Combustion	Biomass (Wood Pellet/Chips) Boiler
Carbon Capture and Storage (CCS)	Complete Post-Combustion CCS
	Partial Post-Combustion CCS (Residual Fuel Streams only)

5.1. ELECTRODE BOILER

Several power-to-heat (PtH) technologies have been developed to address various industrial heating needs. These range from low-temperature heat pump to electric furnaces for the use in petrochemical cracking and metal industries at a temperature up to 3000°C [67–68]. Technologies that are commonly applicable for high temperature (between 250 to 350°C) steam generation are limited to electric boilers and electrode boilers [69]. Electric boiler technology, which works with a resistance heating principle, is capable for heating gases to a temperature up to 600°C. It has, however, a relatively small capacity, up to 5MWe [67]. Such low capacity is significantly lower than the two steam boilers currently employed in the Botlek site, which both have a thermal output of 115MW, while the annual steam demand in the Maasvlakte site ranges up to 8PJ. As such, electric boiler is excluded from the research scope. The following focuses only on the electrode boiler as a drop-in replacement for steam generation.

The commercially available electrode boiler is capable of producing saturated steam of up to 350°C [67–69]. The maximum capacity of a single boiler is significantly larger than an electric boiler, reaching up to 70 MWe [67–69], or even 90 MWe [70]. Its operating principles rely on the conductive and resistive properties of water to carry electric current and to generate steam. To further explain, the electricity flows through the electrodes generate an electric field which causes the water molecules to move at high speed, which in turn generates heat for steam production [71]. The electrode boiler technology is said to have achieved a technological readiness level of 9 [67]. The following tables are summaries of the technical and economical parameters for the electrode boiler technology.

Table 16: Technical parameters for the electrode boiler technology

Parameter	Unit	Value (Range)	References
Availability	%	97 (up to 100)	[67]
Efficiency	%	99.9 (95 – 99.9)	[67–69]
Technical Lifetime	Years	15	[70]

Table 17: Economic parameters for electrode boilers

Parameter	Unit	Value [18] (Range)	References
Investment Cost[19] *Reference capacity: 70MW$_e$*	€$_{2018}$/kWe	75.4 (75.4 – 123.3)	[70–72]
Fixed O&M Cost	€$_{2018}$/kWe/year	47 (1.4 – 47)	[70–72]
Variable O&M Cost	€$_{2018}$/MWh	0 (0 - 0.2)	[70–72]
Fuel Cost	-	Electricity cost (see Appendix A.4)	

5.2. HYDROGEN COMBUSTION

Hydrogen-based combustion is one of the promising options in decarbonising high-temperature heat production. Hydrogen (H_2) combustion readily replaces steam production from gas-fired steam boilers or other fossil fuel-based CHP facilities without requiring much modification to the main process configurations. Additional investment is, however, needed for boiler retrofitting or new boiler installation. The hydrogen feedstock may be produced on-site or sourced from external production site, which requires additional investments for a new production facility or possibly the construction of a new pipeline connection.

Hydrogen can be produced from fossil-based (i.e. natural gas, coal) and renewable-based (i.e. biomass, renewable electricity) energy, through a wide variety of production routes. Nonetheless, the decarbonisation potential of a hydrogen-based steam production varies greatly, depending on the primary energy input and the chosen production technology. Hydrogen can be further categorised into three "colour" categories, namely grey, blue and green hydrogen, based on the carbon emissions of the production routes. These three categories are as summarised in Appendix A.3.

The decarbonisation option may be realised in LyondellBasell's production sites by installing new hydrogen boilers or by retrofitting the existing gas-fired steam boilers in the Botlek site. A blue hydrogen production project, named H-vision, has been initiated for the Port of Rotterdam industrial cluster whereby a feasibility study has been conducted in 2019. It is proposed that the produced hydrogen will be supplied as energy carriers to the utility and petrochemical companies in the industrial cluster. The H-Vision project paves the way towards large scale production of green hydrogen. Alternatively, hydrogen may be produced on-site for own use. The possibilities of sourcing the hydrogen from the H-vision project, off-site green hydrogen production site, and own hydrogen production through electrolysis are explored.

5.2.1. HYDROGEN BOILER

New hydrogen boilers are required to be installed for the Maasvlakte site. Hydrogen boiler technology for steam generation is said to have achieved a TRL of 9 [73]. The boiler capacity is quoted between 5 to 50 MW through market consultation [74], possibly reaching up to 200 MW [70]. On the other hand, the existing natural gas-fired steam boilers employed at the Botlek site may be retrofitted, reducing the investment costs. Retrofitting is required due to the different combustion characteristics between hydrogen and natural gas combustion, leading to challenges such as changes in heat transfer characteristics, increased NO_x emissions and changes in flue gas composition. The TRL for burner retrofitting is currently at TRL 7 and is projected to

[18] Values used in MAC are based on estimates in [72]

[19] Refers to the total boiler installed cost (TIC). The cost range is re-estimated based on original reference capacities in [70–72], using a scale factor of 0.7

reach commercial readiness by around 2025 [75]. Co-burning of hydrogen with another gaseous mix (i.e. natural gas, furnace gas) could also be done with the hydrogen boiler.

The following tables summarise the technical and economic parameters for both new hydrogen boiler installation and the retrofitting of natural gas boilers. Due to the lack of public data, the technical parameters are assumed the same for both hydrogen boiler and gas-fired boiler retrofitting, unless stated otherwise. The technical lifetime of the retrofitted boiler is constrained by the remaining lifetime of the existing combustor. The variable O&M cost is dependent on the amount of fuel usage and the fuel cost. The fuel cost differs according to the hydrogen sources and is further discussed in the following subsections.

Table 18: Technical parameters for a newly installed hydrogen boiler and the boiler retrofitting

Parameter	Unit	Value (Range)	References
Availability	%	97 (86 – 100)	[74]
Efficiency	%	90	[73], [74]
Technical Lifetime (New boiler)	Years	25	[73]
Technical Lifetime (Retrofitting)	Years	10; as constrained by the remaining lifetime of the existing combustors	

Table 19: Economic parameters for a newly installed hydrogen boiler and the boiler retrofitting

Parameter	Unit	Value (Range)	References
New Hydrogen Boiler			
Investment Cost [20] *Reference Capacity: 50 MW_{th}*	€$_{2018}$/kW_{th}	104 (89 – 119)	[74]
Fixed O&M Cost	€$_{2018}$/kW_{th}/year	17.5 (15 – 20)	[74]
Retrofitting of Existing Natural Gas Boiler			
Investment Cost [21, 22] *Reference Capacity 115 MWth*	M€$_{2018}$	3.017	[75]
Fixed O&M Cost	€$_{2018}$	3% of total investment	[75]

5.2.2. HYDROGEN PRODUCTION: H-VISION – A BLUE HYDROGEN PROJECT

One of the possible near carbon-neutral hydrogen sources is from the blue hydrogen production. The H-Vision project is a large-scale blue hydrogen project kickstarted for the Port of Rotterdam industrial cluster [76]. The project is ambitioned to start its operations in late 2025 and running at full capacity in 2030. The H-Vision is touted as the near-term decarbonisation option and the infrastructure built will pave the way to transitioning into green hydrogen usage in the future (see 5.2.3).

The blue hydrogen produced from H-Vision would be mainly used to power industrial processes in refineries and power plant [76]. The current preferred technology, high-pressure Auto Thermal Reforming (ATR), offers advantages in terms of economies of scale and operational flexibility over the other technologies. Hydrogen will be produced as the energy carrier by reforming both the high-caloric natural gas and residual

[20] The investment cost is re-estimated based on the original reference capacity in [74], using a scale factor of 0.7.

[21] The investment cost includes the equipment costs as well as engineering design (5% of total cost), project construction and management (3% of total cost), removal (5% of total cost), labour (10% of total cost), commissioning (2% of total cost) and estimated contingency (12% on top of all other costs).

[22] The investment cost is re-estimated based on the original reference capacity in [75], using a scale factor of 0.7, scaling up to match the capacities of the existing steam boilers.

gases from the industrial processes. Nonetheless, carbon capture & storage is required in coupling with the ATR. The project will take advantage of the PORTHOS project, storing the captured CO_2 under the North Sea. The PORTHOS project is briefly described in 5.4.2. In addition, an additional gas network is expected to be installed to allow the flow of flue gases from industrial production facilities to the blue hydrogen production plants, as well as to feed the hydrogen gas to the industrial facilities. The coupling of ATR and CCS results in a reduced emission factor of 0.028 tCO_2/MWh of H_2 [76].

The H-Vision project does not only offer a near carbon-neutral fuel for LyondellBasell's operations but also offers an alternative use of the unavoidable residual fuel gas produced from the industrial processes. The maximum scope, which assumes participation of LyondellBasell and a number of additional users in comparison to the reference scope defined in [76], expects an installed hydrogen production capacity of 3820 MW and 1000MW of hydrogen storage in a salt cavern.

The following table shows the technical and economic parameters assumed in estimating the levelised cost of blue hydrogen (LCOH)[23]. The LCOH is calculated based on the maximum scope, assuming a 100% load factor[24] by 2031. This is done in addition to the economic analysis conducted by Deltalinqs[25] [76], to allow more coherent assumptions (i.e. discount rate, fuel prices) in the overall MACC calculations in this research. The fuel cost used in the MAC analysis considered a 15% profit margin, on top of the LCOH.

Table 20: Technical parameters of the H-vision Project

	Unit	Maximum Scope
Total hydrogen demand (Maximum)	MW	5202
Installed Hydrogen production capacity	MW	3820
Maximum natural gas supply to the hydrogen plant	MW	3620
Required electricity	MWh_e/MWh output	5.3%
CO2 Captured per year (Maximum)	Mt/year	9.9

Table 21: Economic parameters of the H-vision Project

	Unit	Maximum Scope
Total plant cost for hydrogen production [a]	$M€_{2018}$	1538.7
Salt cavern storage capital expenditure (CAPEX) [a]	$M€_{2018}$	186.3
NG supply pipeline CAPEX [a]	$M€_{2018}$	122.6
RFG transfer pipelines CAPEX [a]	$M€_{2018}$	27.3
NG & RFG compressors CAPEX [a]	$M€_{2018}$	37.2
Hydrogen distribution CAPEX [a]	$M€_{2018}$	71.3
Fixed O&M for hydrogen production [b]	$M€_{2018}$/year	62
hydrogen distribution operating expenditure (OPEX) [b]	$K€_{2018}$/year	713
Hydrogen Storage OPEX [b]	$M€_{2018}$/year	6.9
CO2 Transport and Storage Tariff [a]	$€_{2018}$/ton	20 (17 – 22)
Connection Cost of the National Hydrogen Backbone [b]	$M€_{2018}$/year	1.94

[a] *based on Table 6.10 in* [76]; [b] *based on Table 6.A in* [77]

[23] The levelised cost of hydrogen takes into account of the CAPEX and OPEX of the reformers, as well as the network and distribution costs of the natural gas, residual fuel gas and hydrogen.
[24] A 50% load factor is assumed for the year 2026, increasing to 100% in 2031. It is noted that hydrogen production may instead be operated in a flexible manner, depending on the electricity price [77].
[25] As calculated in [76], the reference scope allows a maximum carbon reduction 3 MT of CO_2, with carbon mitigation cost ranges between 86 and 146 € per tonne of CO_2, depending on the macroeconomic scenarios assumed.

5.2.3. HYDROGEN PRODUCTION: OFF-SITE LARGE-SCALE GREEN HYDROGEN PRODUCTION

Alternatively, hydrogen may be purchased from large scale, off-site green hydrogen production. Green hydrogen is generally produced through water electrolysis process, by which carbon-neutral, renewable electricity is used to separate water molecules into hydrogen and oxygen in a 1:8 weight ratio, allowing a 100% CO_2 reduction. This production route also avoids the use of fossil fuel, in comparison to the blue hydrogen which utilises natural gas as the main feedstock. A cost analysis was conducted by Navigant [74] in 2019, with a concluded range of green hydrogen price between 3000 to 8000 €/tonne of H_2. The high uncertainty is mainly due to the wide range of investment costs determined through both literature review and market consultation. Other cost components included in the cost analysis are energy costs (€30 – 70/MWh), OPEX (3 – 5% of CAPEX) and oxygen selling price (13 – 40 €/ton of O_2). It is, however, projected that the levelised cost of hydrogen would decrease rapidly in the next decades, reaching parity with the production cost of blue hydrogen. A recent report from Hydrogen Council [78] projected that the cost of green hydrogen could drop to about USD 1 - 1.50 per kg in optimal regions, and USD 2 - 3 per kg under average conditions. Such cost improvement is driven by strong reductions in electrolyser CAPEX, through the deployment of about 70 GW of electrolyser capacity worldwide. Similar projections trend is forecasted by IRENA [79], though the reduction is less rapid with production cost ranges between USD 1.75 to 3.25 per kg (see Figure 28 in Appendix A.3).

Table 22: Current and projected levelised cost of green hydrogen

Parameter	Unit	Value (Range)			References
		Current	2030	Constant Baseline Value for MACC	
Levelised Cost of Hydrogen	€/ ton of H_2	3,000 – 8,000	880 – 2,860[26]	1750[27]	[74–78–79]

5.2.4. HYDROGEN PRODUCTION: ON-SITE ELECTROLYSIS

On-site self-production of hydrogen may be performed by means of water electrolysis. The commercially available electrolysis technologies include the Alkaline Electrolysis (AEL) and the Polymer Electrolyte Membrane (PEM) technologies, with a TRL of 9 and 8 respectively [80–81]. Other variants are, for example, solid oxide electrolysis cell (SOEC) with a TRL of 5 and Alkaline Exchange Membrane (AEM) electrolysis. The latter is still currently at laboratory scale [82]. Hence, only the PEM and AEL are considered for decarbonisation implementation at LyondellBasell's production sites. The levelised costs of the hydrogen production (LCOH) from the two technologies are first calculated and used as the fuel cost input parameter in the MAC curve analysis.

5.2.4.1. ALKALINE ELECTROLYSIS (AEL)

In an Alkaline Electrolysis (AEL) technology, the electrolysis takes place in the cells containing the electrolyte solution (i.e. potassium hydroxide (KOH)) and the electrodes. The electrodes are made up of nickel or porous metal structures [83], and the two compartments are separated using a diaphragm. These electrolytic cells are connected in series to form a "stack". AEL is operated within a temperature range between 60 to 70 °C [82], and the hydrogen gas is produced typically at 30 bar. The pressure range is expected to increase to 40

[26] USD to € conversion factor of 0.88

[27] Assumed average values for all types green hydrogen production sources between 2030 and 2050 in [79]

bar by 2030 and 70 bar by 2050 [83]. The stack capacity is commercially available at between 1 – 5 MW [82]. Multiple stacks can be linked together to meet the required production capacity, going up to 400 MW [80].

While currently at a TRL level of 9 [81], many developments are still expected of the AEL technology. These are in terms of the stack technical lifetime, as well as the investment cost. The following tables provide a summary of the techno-economic parameters for the AEL technology, at its current development stage and projected performance in 2030.

Table 23: Technical parameters for the Alkaline Electrolysis (AEL) Technology

Parameter	Unit	Value (Range)		References
		Current	2030	
Availability	%	97	97	[84]
Efficiency	%	60 – 65	67	[84]
Installation Technical Lifetime	Years	20 – 40	25 (20 – 40)	[84]
Stack Technical Lifetime	Hours	60,000 (~7 years)	80,000 (~9.5 years)	[84]

Table 24: Economic parameters for the Alkaline Electrolysis (AEL) Technology

Parameter	Unit	Value (Range)		References
		Current	2030	
Equipment Investment Cost	$M€_{2018}/MW_{H2}$	0.97 – 1.89	0.71 (0.63 – 1.47)	[84]
Stack Cost		30% of total investment cost	30% of total investment cost	[84]
Civil Work & Connection Cost[28]	$M€_{2018}$	7.2	7.2	[80]
Fixed O&M Cost	$M€_{2018}/MW_{H2}$/year	0.03	0.02	[84]

5.2.4.2. POLYMER ELECTROLYTE MEMBRANE (PEM)

In contrast to AEL, the ionic transfer is conducted over a solid polymer in a PEM cell [80]. Similar to AEL, the cells are connected in series to form a "stack". PEM is operated within a temperature range between 60 to 70 °C [82]. The hydrogen gas can be produced at a pressure of 5 - 50 bar, potentially to 110 bar in 2050 [80–83]. The stack ranges between 0.25 and 5 MW, and multiple stacks can be linked together to meet the required production capacity [80].

PEM technology is currently of lower TRL than AEL, at TRL of 8 [80]. The investment costs are expected to decrease over time while improvement is also expected of the stack lifetime. The following tables provide a summary of the techno-economic parameters for the PEM technology, at its current development stage and projected performance in 2030.

[28] Includes electrical connection cost to the national power grid

Table 25: Technical parameters for the Polymer Electrolyte Membrane (PEM) Technology

Parameter	Unit	Value (Range)		References
		Current	2030	
Availability	%	97	97	[80]
Efficiency	%	58 – 65	65 (64 – 65)	[80]
Installation Technical Lifetime	Years	20 – 30	25 (20 – 30)	[80]
Stack Technical Lifetime	Hours	40,000 (~5 years)	60,000 (~7 years)	[83]

Table 26: Economic parameters for the Polymer Electrolyte Membrane (PEM) Technology

Parameter	Unit	Value (Range)		References
		Current	2030	
Equipment Investment Cost	$M€_{2018}/MW_{H2}$	1.36 – 2.43	1.2 (0.41 – 1.73)	[80]
Stack Cost		40% of total investment cost	40% of total investment cost	[80]
Civil Work & Connection Cost[29]	$M€_{2018}$	7.2	7.2	[80]
Fixed O&M Cost	$M€_{2018}/MW_{H2}$/year	0.06 – 0.07	0.05 (0.02 – 0.05)	[80]

5.3. BIOMASS COMBUSTION

Biomass may also be used as a carbon-neutral replacement fuel, allowing complete decarbonisation. This is provided that the sourced biomass adheres to the sustainability criteria in accordance with the EU Directive [85]. There is a wide variety of biomass technologies applicable for heating applications, using biomass in solid, liquid and gas forms, as detailed in [86]. As reported in [87], the majority of the biomass usage in industrial furnaces or boilers are woody biomass, such as wood chips or pellets. The wood chips may be sourced domestically or imported from agricultural and forestry residues, as well as from industrial residues (i.e. sawdust and wood scrap from wood processing industry). Wood pellets can be sourced domestically but are primarily imported from abroad with the United States as the main supplier [87].

The following and the MAC curve analysis consider the use of solid biomass boilers at the Botlek and Maasvlakte sites as an alternative steam generation system. Facilities such as biomass storage system, flue gas cleaning etc. may be needed, in addition to the boiler. The following tables provide a summary of the techno-economic parameters for an industrial wood pellet steam boiler.

Table 27: Technical parameters for an industrial wood pellet steam boiler

Parameter	Unit	Baseline Value (Range)	References
Availability	%	97	[86–88]
Efficiency	%	90	[86–88]
Technological Readiness Level (TRL)	-	9	[88]
Technical Lifetime	Years	15 (12 – 15)	[86–88]

[29] Includes electrical connection cost to the national power grid

Table 28: Economic parameters for an industrial wood pellet steam boiler

Parameter	Unit	Baseline Value[30] (Range)	References
Investment Cost[31] *Reference Capacity: 50 MW* [32]	€$_{2018}$/kW$_{th}$	440 (440 – 585)	[70–86]
Fixed O&M Cost	€$_{2018}$/kW$_{th}$	44 (5.9 – 44)	[70–86]
Variable O&M Cost	€$_{2018}$/kWh$_{th}$	0.0034 (0.0008 – 0.0034)	[70–86]
Fuel Cost		Biomass cost (see Appendix A.4)	

5.4. CARBON CAPTURE AND STORAGE (CCS)

Carbon capture and storage (CCS) allows the continued usage of fossil fuels in LyondellBasell's operations, whilst achieving deep decarbonisation. The implementation of CCS, however, requires a series of infrastructure to be developed, including carbon capture installation at the industrial sites, transport network (i.e. pipeline, truck), subsequently the reuse of the captured carbon (e.g. in greenhouses) and/or permanent storage deep in geological formations. Currently, a CO_2 transport & storage project, PORTHOS, is being initiated as collective infrastructure for the Port of Rotterdam industrial cluster [89], as further detailed in the following subsection.

There are three main categories of carbon capture technologies, namely post-combustion, pre-combustion and oxyfuel combustion [90], as briefly introduced in Appendix A.3. An analysis has been conducted by Berghout et. al. in 2015 [91], investigating the cost-effectiveness of the different CCS configurations for the Botlek industrial site. The different configurations consider not only the three main types of capture technologies but also the possible industrial synergies between companies. Nonetheless, the following sub-sections and the MAC curve analysis consider only the independent carbon-capturing effort by LyondellBasell through the use of post-combustion carbon capture technology. The captured CO_2 will make use of the PORTHOS project, to be transported and stored under the North Sea.

5.4.1. POST-COMBUSTION CCS

In consideration of LyondellBasell's existing steam boilers at the Botlek site, post-combustion capturing technology is chosen as it is the preferred option for retrofitting existing plants [90]. On the other hand, newly installed gas-fired steam boilers coupling with post-combustion CCS is considered as one of the possible decarbonisation options for the Maasvlakte site. The technical and economic parameters for gas-fired steam boilers are as presented in A.3. While oxy-fuel combustion may instead be considered for a new installation, this, however, requires costly and energy-intensive oxygen production. Particularly, it is suggested that gas-fired and oil-fired boilers are more suitable for post-combustion technologies, due to its relatively high hydrogen ratio in the fuel, leading to high oxygen demand [92].

Post-combustion carbon capture technologies may be further differentiated based on the CO_2 separation methods. For example, adsorption, absorption and membrane separation methods [90]. The chemical absorption technology based on monoethanolamine (MEA) is suggested as the most promising separation

[30] Baseline values are based on estimates in [86]

[31] The cost range is re-estimated based on original reference capacities in [70–86], using a scale factor of 0.7. As noted in [70–86], the cost includes the relevant equipment costs (biomass handling system, flue gas cleaning etc.) and the construction costs

[32] It is noted in [128] that biomass boiler capacity ranging up to 200 – 300 MW is available for CHP. Typical industrial boiler is however around 20 MW, possibly up to 50 MW.

method, achieving a capture efficiency of 90 % [90–91–93]. Amine-based capturing technology also has a TRL of 9 [94]. The MEA sorbent is used to separate the CO_2 from the flue gas, which then regenerated through a stripping or regenerative process [90]. Additional heat and electricity are required for the capturing process. Following the initial capturing, it is expected that the CO_2 stream is compressed to a pressure of 35 bar for it to be transported through the PORTHOS CO_2 grid [95]. The following tables provide a summary of the technical and economical parameters for the carbon capturing and compression process, leading up to the connection with PORTHOS network. The reference capturing technology is based on the 30% MEA absorption method.

The MAC curve analysis considered two different decarbonisation configurations, namely the full post-combustion CCS and partial post-combustion CCS. For the full post-combustion CCS configuration, it is assumed that the all required steam is supplied by the (existing or new) fossil-fuel-based boilers, utilising both the residual fuel streams and natural gas as fuel input. The associated emissions are then captured and stored, given the capture efficiency. The partial configuration considered the combustion of residual fuel streams only, then the capturing and storing of the emissions. The calculation is further explained in A.3.

Table 29: Technical parameters for post-combustion carbon capturing, purification and compression

Parameter	Unit	Value (Range)	References
Availability	%	97 (84 – 97)	[91]
CO_2 Capture Efficiency	%	90	[91]
Technical Lifetime	Years	25 (15 – 25)	[91]
Regeneration heat required for carbon capturing	GJ_{LHV}/tCO_2	4.0 (3.5 – 4.0)[33]	[91]
Electricity for carbon capturing	GJ_e/tCO_2	0.3 (0.1 – 0.3) [33]	[91]
Electricity for CO_2 compression	GJ_e/tCO_2	0.45	[95]

Table 30: Economic parameters for post-combustion carbon capturing, purification and compression

Parameter	Unit	Value (Range)	References
CAPEX[34] *(Reference CO_2 Capture Capacity: 800 kt/year)*			
- **Stack Modification**	$M€_{2018}$/stack	0.1	[91]
- **SCR/FGD[35] units**	$€_{2018}/(tCO_2/year)$	26	[91]
- **CO2 Capturing Equipment**	$€_{2018}/(tCO_2/year)$	79	[91]
- **CO2 treatment & compression**	$€_{2018}/(tCO_2/year)$	12	[91]
OPEX			
- **Maintenance**	-	3% of Total Plant Cost	[91]
- **Labour, Taxes & Insurance, Administration & Overhead**	$€_{2018}/tCO_2$	2.45	[91]
- **Connection Cost[36]**	$€_{2018}/tCO_2/year$	4.3	[95]
- **Others[37]**	$€_{2018}/tCO_2$	2.7	[91]

[33] Lower carbon concentration, which is the case for oil or gas-fired systems, requires higher regeneration heat and electricity.

[34] The costs (except for the stack modification cost) are re-estimated based on original reference capacity of 1 Mt/year in [91], using a scale factor of 0.7. The reference capacity, 800kton/year, shown in the table are used for the complete CCS configuration for both sites. Reference capacities of 200 kton/year and 400 kton/year are used for the partial CCS configuration, for Maasvlakte and Botlek, respectively. The CAPEX refers to the total plant cost.

[35] SCR: Selective catalytic reduction; FGD: Flue gas desulphurisation

[36] Assumed 3km connection from the industrial site to the PORTHOS CO_2 grid

[37] Includes water usage and chemical costs [91]

5.4.2. PORTHOS

The Port of Rotterdam CO_2 Transport Hub and Offshore Storage (PORTHOS) project aims to set up a collective transport and storage facility for the industrial companies in the Port of Rotterdam [89]. The individual companies are expected to perform their carbon capturing, subsequently supplying to the main CO_2 grid running through the port area. The CO_2 will be compressed in a centralised station, before being transported to an offshore platform, through an offshore transport network. The compressed CO_2 will then be pumped into the porous sand reservoir, more than 3 km beneath the North Sea seabed. Alternatively, the CO_2 grid may be connected to sites where CO2 may be utilised (i.e. greenhouses). A final investment decision is expected in late 2021, with expected initial operations in late 2023. As described in 5.2.2, PORTHOS will also be one of the main components of the H-Vision project.

The industrial companies supplying CO_2 to the collective PORTHOS infrastructure are expected to pay a processing tariff, inclusive of both storage and transport fees. Current estimate provided by PBL suggested a processing tariff of 60 €/tCO_2[38] [95]. Contrarily, H-Vision feasibility study suggested a range between 17 to 30 €/tCO_2, calculated based on a report by EBN and Gasunie, and using TNO's in-house model [76]. The main MAC curve analysis assumed a processing tariff of 24 $€_{2018}$/tCO_2, and a sensitivity analysis was conducted for tariff ranging from 17 to 60 $€_{2018}$/tCO_2.

Table 31: Estimated processing tariff for the PORTHOS project

Parameter	Unit	Value	References
Processing Tariff	$€_{2018}$/ ton of CO_2	60	[95]
		24 (17 – 30)	[76]

[38] Calculated based on occupancy rate of 70%

Chapter 6: Results of the Marginal Abatement Cost (MAC) Curve Analysis

This chapter illustrates the results of the marginal abatement cost (MAC) curve analysis for the two production sites, in two separate site-specific MAC curves. As detailed in Chapter 5, the MAC curve analysis considered only a limited number of decarbonisation options for the steam supply. Nevertheless, this addresses at least 88% of the scope 1 and 2 emissions for both production sites. The remaining scope 2 emissions can be attributed to their electricity consumption. The other emissions, such as those resulted from the flaring, catalytic converter and thermal combustor systems, are limited. As previously detailed in 2.3.1, the MAC curve analysis employed a "frozen technology" baseline as the reference situations, assuming no changes to the energy technologies used in the reference situations between now and the end of the analysis period. This has also assumed that the production activity levels and the steam demand to remain constant.

The reference situations are as described in 4.1.3 and 4.2.7, as well as depicted graphically in Figure 16. This research and the MAC analysis have restricted the scope to consider scenarios where decarbonisation effort is made solely by LyondellBasell. It is, however, likely that the external utility partners (i.e. MPP3, UCML) may have alternative decarbonisation plans, resulting in reduction of LyondellBasell's scope 2 steam-related emissions.

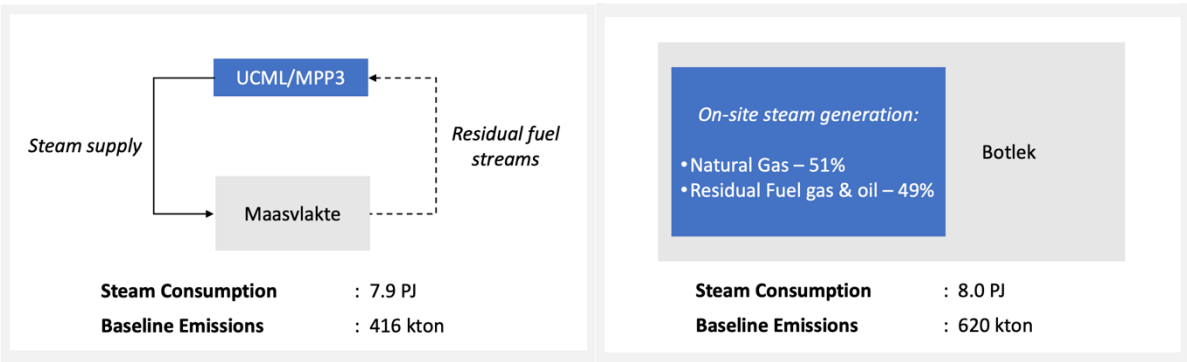

Figure 16 (left): Reference situation for Maasvlakte production site, where the steam is supplied by the neighbouring CHPs; (right) Reference level for Botlek production site. The production site is assumed to be self-sufficient by generating its own steam supply, utilising its residual fuel streams and natural gas as fuel input.

The calculation methods and assumptions used in assessing the technical abatement potential and the marginal abatement costs are as detailed in 2.3.1. The technical and economic parameters of the decarbonisation options are as detailed in Chapter 5: Decarbonisation Options. The quantitative results are shown in the form of MAC curves and described in the following sub-chapters.

6.1. MAASVLAKTE SITE

The MAC curve calculated for the Maasvlakte site is as illustrated in Figure 17 below. Two sets of MACs are presented for the decarbonisation options, with and without considering the carbon price. The results are also summarised in Table 44 in Appendix A.5.

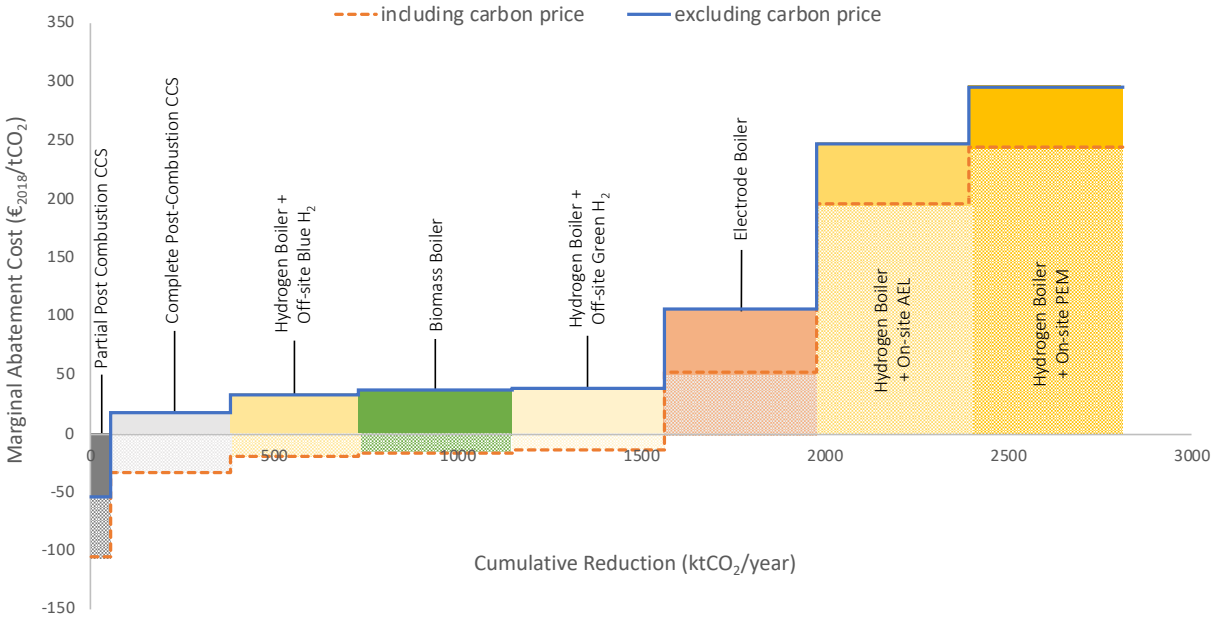

Figure 17: Figure showing the MAC curve for the Maasvlakte production site. The orange dotted line and patterned bars refer to the marginal abatement cost considering the carbon price. The blue solid line and solid coloured bars refer to the marginal abatement cost without considering the carbon price.

It can be noted that the technology ranking, in terms of cost-effectiveness, remains unchanged in both sets of MACs, with or without the carbon price. Notwithstanding, most of the decarbonisation options are more expensive than the reference technology in the absence of carbon price. The only exception is the partial CCS configuration, which considers the utilisation of residual fuel streams on-site (see Table 35) and the subsequent capturing of the associated emissions. The abatement potential is however very limited, only at 13%. The reference technology for Maasvlakte site refers to an external gas-fired CHP, with a constant steam purchasing price of 13 €$_{2018}$/GJ of steam.

The inclusion of the carbon price[39] has resulted in a total of five decarbonisation options with a negative MAC. Meaning, the options are cheaper than the reference technology. The MACs of all options have also reduced by 52-54 €$_{2018}$/tCO_2. The most cost-effective option remains the partial CCS configuration, followed by the complete CCS configuration[40], which results in a 79% abatement. Although penalised by the economies of scale, the partial CCS configuration remains at a lower MAC than full CCS configuration as the residual fuel streams are considered zero price and no natural gas is used in the assumed configuration. Together with the high steam purchasing price, these hence resulted a highly negative MAC. Hydrogen Boiler + offsite blue H_2, Biomass Boiler, and Hydrogen Boiler + offsite green H_2 are at a close competition, with a MAC difference of less than 3 €$_{2018}$/tCO_2 between one technology and the next in rank. Besides, It can be observed that highly electricity-dependent technologies, particularly hydrogen boiler with on-site AEL and

[39] This considers any mitigated carbon emissions as a form of cost-saving, either due to avoided carbon penalty or increased revenue by selling carbon certificates.

[40] The complete CCS configuration considers on-site steam generation using both the residual fuel streams and natural gas, followed by post-combustion carbon capturing. This hence requires the installation of new boilers.

PEM electrolysers are poorly ranked, particularly due to the high electricity price and low conversion efficiencies.

Except for the partial CCS configuration, the decarbonisation options presented in the MAC curve can be seen as competing technologies. These options are analysed based on a 100% technology replacement, yielding a (near) net-zero decarbonisation. On the other hand, the partial CCS configuration, with a net useful steam output of 1.41 PJ, may be implemented in combination with the other technology of choice, allowing deeper decarbonisation. For example, the remaining required steam supply of 6.47 PJ can be supplied by the biomass boiler, electrode boiler or the hydrogen boiler. These combinations shall allow up to a 95% reduction, due to incomplete carbon-capturing efficiency of 90%. The combinations of partial CCS configuration and the other technologies have resulted in different overall MACs. These combinations are further discussed in 7.2.1. Alternatively, a complete CCS configuration may instead be considered, which remains the most cost-effective option at deep decarbonisation.

6.2. BOTLEK SITE

Figure 18 below illustrates the MAC curve calculated for the Botlek site. Two sets of MACs are presented for the decarbonisation options, with and without considering the carbon price. The results are also summarised in Table 45 in Appendix A.5.

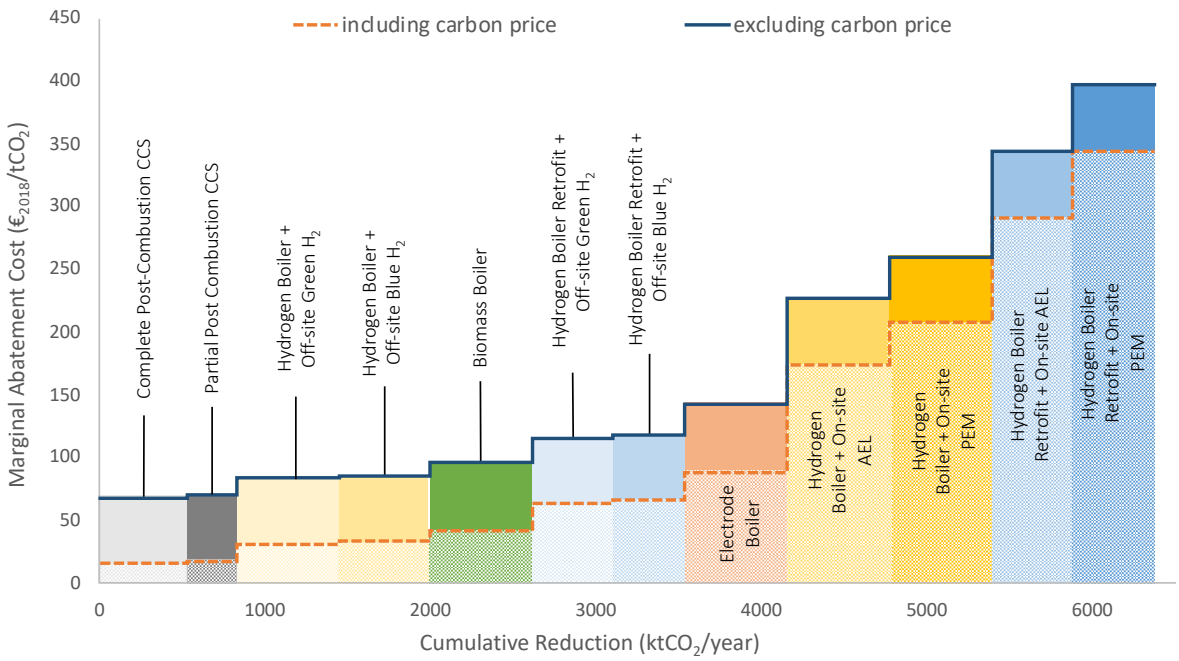

Figure 18: Figure showing the MAC curve for the Botlek production site. The orange dotted line and patterned bars refer to the marginal abatement cost considering the carbon price. The blue solid line and solid coloured bars refer to the marginal abatement cost without considering the carbon price.

The technology ranking, in terms of cost-effectiveness, remains unchanged in both sets of MACs. An additional four options have been considered for the Botlek production site. Specifically, retrofitting options are considered to allow hydrogen from various sources to be used in the combustors of the recently installed gas-fired boilers (as already described in 4.2.7.). Nonetheless, the retrofitting options are consistently more expensive than the complete replacement with new hydrogen boilers. The retrofitting options assumed a technical lifetime of only 10 years, as constrained by the remaining lifetime of the existing combustors. The effect of the assumed technical lifetime is later discussed in 7.1.2.

All decarbonisation options are more expensive than the reference technologies replaced, with or without considering the carbon price. Notwithstanding, the inclusion of carbon price substantially reduces the MACs by around 52-54 $€_{2018}/tCO_2$. Compared to the MAC results for the Maaslakte site, the MACs of the same decarbonisation options differ greatly between the two results. Besides, some changes to the technology ranking can be observed. These are attributable to the different reference situations assumed, which differ in both reference costs and baseline emissions. The high steam purchasing price assumed for the Maasvlakte site allows the options to have a much lower MAC, though slightly compensated by the lower carbon intensity of the steam supply. Nevertheless, a similar trend can be observed, with CCS technologies being the cheapest options and highly electricity-dependent technologies being the most expensive.

The complete CCS configuration has the lowest MAC and is around 2 $€_{2018}/tCO_2$ less expensive than the partial CCS configuration. The higher MAC of the partial CCS configuration is due to unfavourable economies of scale. Similar to the analysis performed for the Maasvlakte site, the decarbonisation options, with the exception of partial CCS configuration and hydrogen retrofitting options, are analysed based on a 100% technological replacement. The partial CCS configuration may be combined with the other technologies, allowing a maximum combined abatement of 91%. These are further discussed in 7.2.1. Nevertheless, the complete CCS configuration is still the cheapest option for deep decarbonisation.

CHAPTER 7: SENSITIVITY ANALYSIS & DISCUSSION

The Marginal Abatement Cost (MAC) curves shown in Chapter 6 illustrate the MACs of the decarbonisation options and their technology ranking, in terms of cost-effectiveness. However, the results are sensitive to the cost and technical parameters assumed in the analysis. The MAC curve analysis has been conducted using data relevant to the Netherlands and the year 2030, whenever possible, to provide the most representative results. Nonetheless, several parameters are of high uncertainty.

Particularly, the carbon price and fuel price trajectories well into the next 30 years are highly uncertain. For instance, two different pricing trajectories have been provided by the WLO Low and WLO High scenarios, depending on the degree of global climate commitment. Other uncertain factors include steam purchasing price for the Maasvlakte site and the CCS processing tariff. The sensitivity of the MACs and the technology ranking due to these various factors are further analysed and discussed in 7.1.

The MAC curve methodology allows comparison between the different decarbonisation options to be made, relative to the reference situation, in terms of the cost-effectiveness. It also allows a simplistic, straightforward graphical representation of the results – an efficient tool for results communication. Nevertheless, the usefulness of the methodology in informing the most-appropriate decarbonisation pathway or options is often criticised. For example, it lacks the consideration of the non-economic factors, which might hinder the implementation of the technologies. In light of that, this chapter also critically discusses the shortcomings of the methodology and how they might impact the results presented in Chapter 6. The MAC curve analysis is also complemented by a qualitative discussion on the non-economic factors, that are relevant for the five most cost-effective options. This provides a more comprehensive view of their implementation feasibility. Notwithstanding, this research poses several general limitations, as further discussed in this chapter.

7.1. SENSITIVITY ANALYSIS

7.1.1. STEAM PURCHASING PRICE (MAASVLAKTE SITE)

A constant steam purchasing price of 13 $€_{2018}$/GJ is assumed as the reference cost for the Maasvlakte site, as determined with reference to prices used in [91] and [96]. The exact purchasing price, possibly agreed in the form of long-term contract between LyondellBasell and the external utility companies (i.e. UCML), is not known. Nevertheless, it is noted that the steam purchasing price may span a wide range between 4 to 20 $€_{2019}$/GJ, as found out by Navigant, through market consultations [74]. This leads to a high parameter uncertainty. A sensitivity analysis has hence been conducted to investigate how the MAC curve results might differ at different steam purchasing prices. The results are presented graphically in Figure 19, on the following page.

As observed from Figure 19, it can be concluded that the MACs of the decarbonisation options are significantly impacted by the assumed steam purchasing price. A high steam purchasing price favours the use of alternative low-carbon options, as this decreases the MACs and potentially brings in positive revenue. The exclusion of carbon price requires a steam price of at least 14.5 $€_{2018}$/GJ for deep decarbonisation option, i.e. Complete Post Combustion CCS, to achieve cost parity with the reference situation. On the contrary, Complete Post-Combustion CCS is cost-effective from steam price as low as 10.5 $€_{2018}$/GJ, when carbon price is taken into consideration. The technology ranking (in terms of cost-effectiveness) is generally intact, in

comparison to the MAC curve shown in Figure 17. The exception is Hydrogen Boiler + Offsite Green H_2, which can be seen overtaking other technologies, at lower steam prices. Nevertheless, as further discussed in 7.3, there is other non-economic barrier for the implementation of Hydrogen Boiler + Offsite Green H_2, despite being one of the most cost-competitive options.

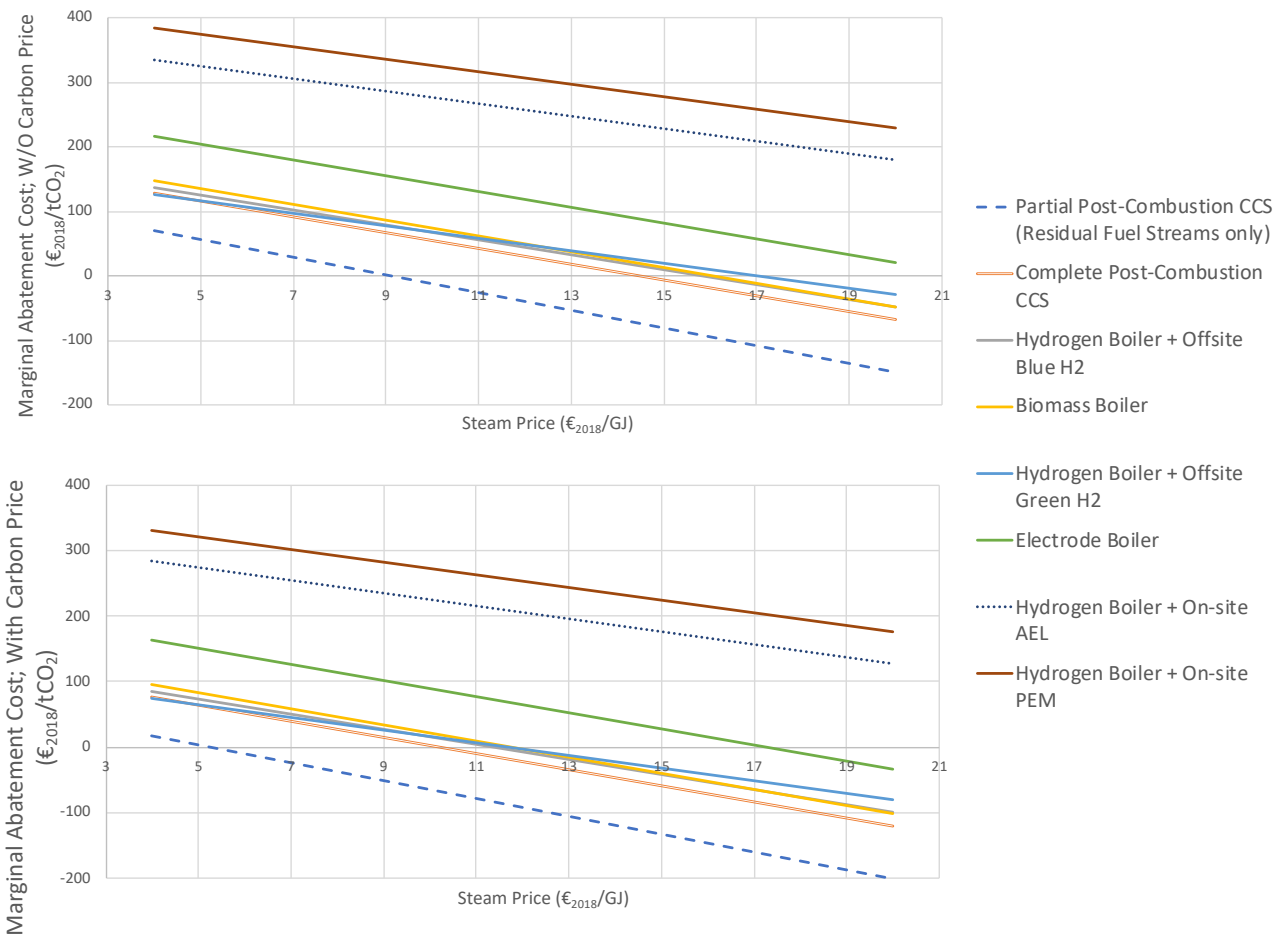

Figure 19: Figures above and below show the MACs at different steam purchasing prices, without and with the carbon price, respectively. The figures share the same legend.

7.1.2. HYDROGEN RETROFIT TECHNICAL LIFETIME (BOTLEK SITE)

As previously noted in 6.2, the hydrogen boiler retrofitting options are consistently more expensive than the complete replacement with new hydrogen boilers (referred to as "reference" in Figure 20). One possible factor is the relatively shorter technical lifetime assumed of 10 years, which is decided based on the predicted remaining lifetime[41] of the existing gas-fired boilers at 2030. Contrarily, a technical lifetime of 25 years is assumed for the new hydrogen boilers. As such, a sensitivity analysis has been conducted to explore how the assumed lifetime may impact the MACs of hydrogen retrofitting options. The results are as shown in Figure 20 and discussed on the following page.

[41] The technical lifetime of a gas-fired boiler is 25 years (see Table 39). The existing gas-fired boilers were installed in 2015, hence a remaining lifetime of 10 years is expected in 2030.

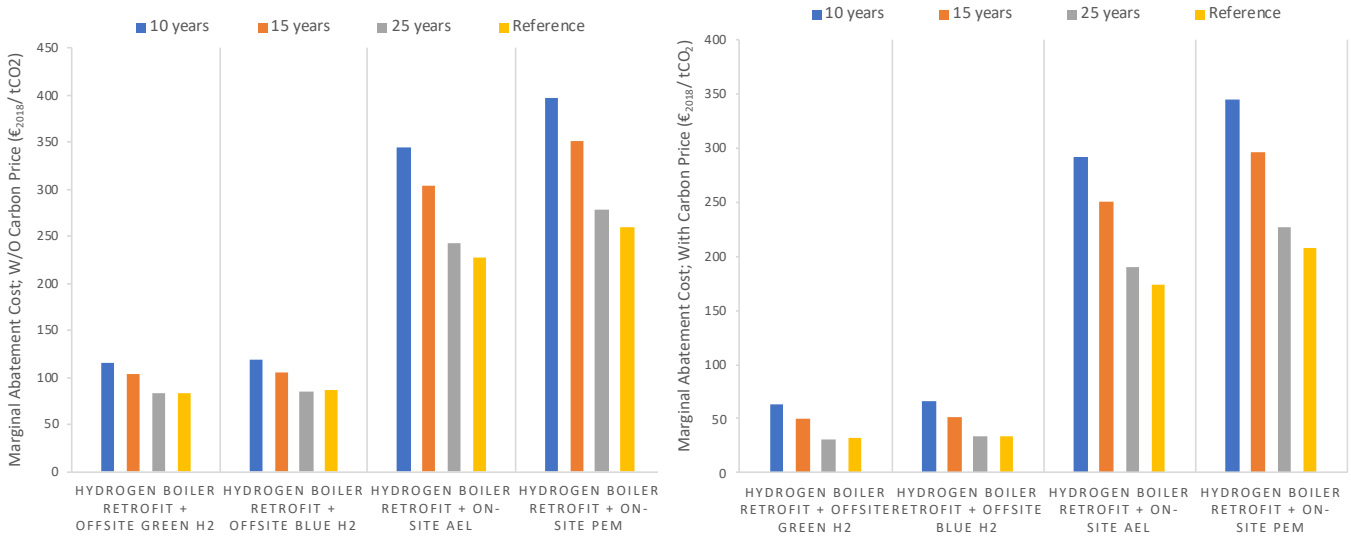

Figure 20: Marginal abatement costs for hydrogen boiler retrofitting options without (left) and with (right) the carbon price. The "Reference" refers to their respective new hydrogen boiler options.

As observed from Figure 20, the assumed technical lifetime has a substantial impact on the MACs. The MACs decrease as a longer technical lifetime is assumed. However, the MACs of the new hydrogen boilers options are similar or still lower than the hydrogen retrofitting options at a comparable technical lifetime. This has resulted from the lower abatement potential of the hydrogen retrofitting options. Specifically, the combustion of hydrogen in the retrofitted boilers decarbonises the steam output that has a relatively lower carbon intensity of 62.6 $kgCO_2/GJ$, as it replaces primarily the use of natural gas, which has a lower emission factor. The carbon intensity of the overall steam output is 69.4 $kgCO_2/GJ$. Though some retrofitting options present a comparably favourable result when a lifetime of 25 years is assumed, it is unlikely that the existing combustors may last for an additional 25 years. Hence, making retrofitting options comparatively undesirable.

7.1.3. DISCOUNT RATE

The MAC results shown in Chapter 6 utilised a discount rate of 6%, with reference to the discount rate used in [74]. It is suggested that the complexities of an industrial project warrant a higher discount rate than solar and wind projects. Nonetheless, a range of 4-8 % are often used in comparable studies [74]. A sensitivity analysis has been conducted to investigate how a different discount rate may affect the results, both in terms of the technology ranking and the MACs. The results are shown in Figure 21 and further explained in the following.

As shown in Figure 21 (on the following page), it can be concluded that the technology ranking is generally not affected by the discount rate assumed, given that the same discount rate is applied for all options. A few exceptions are highlighted by the red circles. For those exceptions, the differences of the MACs between the options are, however, generally small, between 2 to 5 $€_{2018}/tCO_2$. It is also important to note that the MACs of the options are significantly affected by the discount rate. A lower discount rate (i.e. 4 %) favours decarbonisation options with high capital investment, while decarbonisation options with substantial operating costs are more attractive at a higher discount rate.

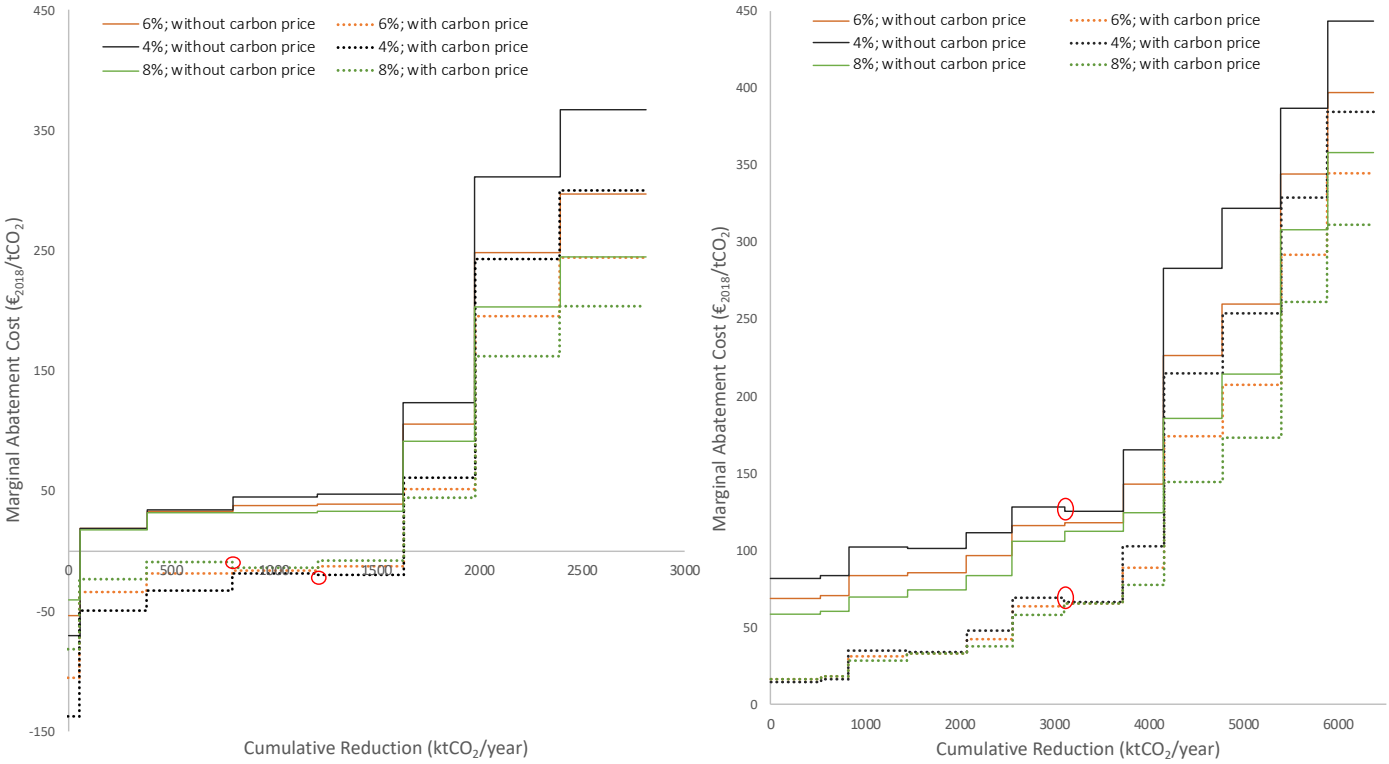

Figure 21: Figures showing the MACs for the decarbonisation options at different discount rates, for Maasvlakte (left) and Botlek (right), respectively. The order of the decarbonisation options in the curve is similar to the order shown in Figure 17 and Figure 18. The red circles highlight the changes in the technology ranking.

7.1.4. CCS PROCESSING TARIFF

Another cost parameter with high uncertainty is the CCS processing tariff. The CCS-related technologies and the H-Vision project are assumed to make use of the PORTHOS project, whereby the captured CO_2 will be sent to the central CO_2 grid for further transportation and storage. Hence, the cost-effectiveness of the technologies is dependent on the processing tariff, chargeable per unit of CO_2 transported and stored. The processing tariff assumed in the MAC analysis is 24 €$_{2018}$/tCO_2 for the CCS-related technologies and 20 €$_{2018}$/tCO_2 for the H-Vision project. These are decided with reference to the tariff range of 17 to 30 €/tCO_2 provided in the H-vision feasibility study [76]. The tariff range is determined based on the study conducted by EBN/Gasunie and TNO's in-house model [76]. It has, however, not been verified by the PORTHOS project. On the contrary, a processing tariff as high as 60 €$_{2018}$/tCO_2 is suggested in [95], following the market consultation and calculated using an infrastructure utilisation factor of 70%. In summary, the possible processing tariff ranges from 17 to 60 €/tCO_2. The impact of such a wide range of processing tariff is presented graphically in Figure 22 and discussed on the following page.

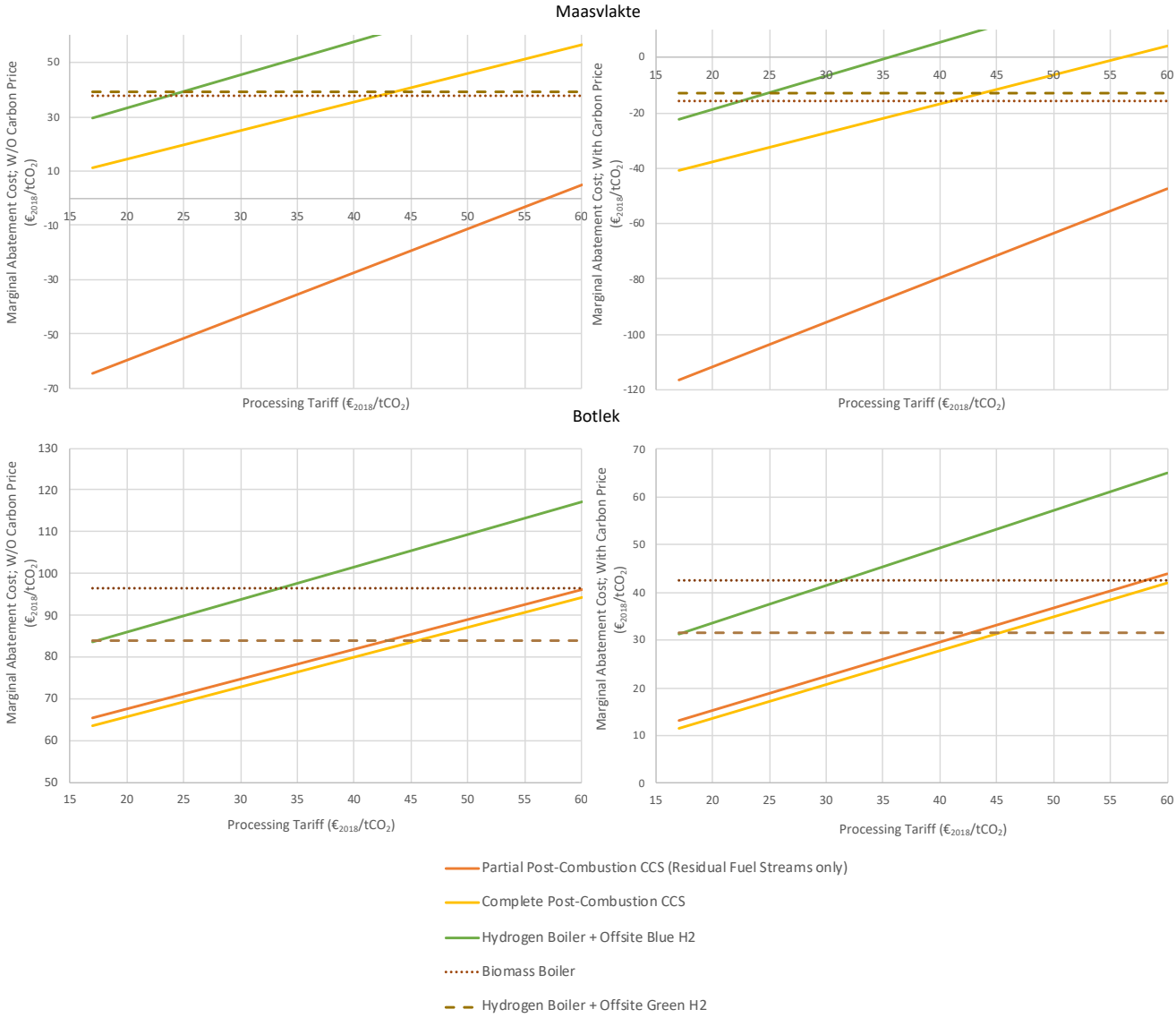

Figure 22: Figures showing how the MACs of the CCS options and Hydrogen Boiler + Off-site Blue H_2 options are impacted by the CCS processing tariff assumed, relative to the Hydrogen Boiler + Offsite Green H_2 and Biomass Boiler options. The figures share the same legend.

The MACs of the three options are highly sensitive to the processing tariff, spanning a difference as large as 34 and 70 €$_{2018}$/tCO_2, for Botlek and Maasvlakte sites, respectively. For the Maasvlakte production site, the partial CCS configuration remains first in rank, while the complete CCS configuration is taken over by both the Biomass Boiler and the Hydrogen Boiler + Green H_2 at a processing tariff rate between 40 to 45 €$_{2018}$/tCO_2. For the Botlek site, the MACs for both the CCS configurations are almost indifferent, with both being taken over by Hydrogen Boiler + Green H_2 at a tariff rate between 42 to 45 €$_{2018}$/tCO_2. On the other hand, the Hydrogen Boiler + Blue H_2 option loses its cost-competitiveness at a relatively low processing tariff, at around 22-25 and 32 €$_{2018}$/tCO_2, for Botlek and Maasvlakte sites, respectively.

7.1.5. PRICING TRAJECTORIES (WLO LOW SCENARIO)

The results shown in Chapter 6 have taken into account the temporal changes in the fuel and carbon prices for the next 30 years. The pricing trajectories assumed in the results shown in Figure 17 and Figure 18 are based on WLO High scenario by PBL [15], assuming a generally high global climate commitment. Nonetheless, the pricing trajectories come with large uncertainties, depending on factors such as climate commitment, geopolitical tensions, supply scarcity etc. The following figures indicate the plausible results at a low global climate commitment, based on the WLO Low scenario projections. The pricing trajectories provided by the two WLO Scenarios are as summarised in Table 43.

In comparison to the results shown in Chapter 6, the different price trajectories based on the WLO Low scenario have impacted the overall technology ranking for both production sites, particularly the first five most cost-effective options. Notably, Biomass Boiler has become the most attractive options for deep decarbonisation. The lower wholesale electricity price has led to a decrease in MACs (excluding carbon price) for electricity-dependent technologies. However in overall, with the exception of Biomass Boiler, the lower carbon price has caused a reduction in the cost-effectiveness of all technologies, when the carbon price is considered in the MACs. The MAC results for the different decarbonisation options are summarised in Table 46 (Maasvlakte) and Table 47 (Botlek). The following discusses the impacts of the pricing trajectories in further details, for the two production sites.

Maasvlakte Site

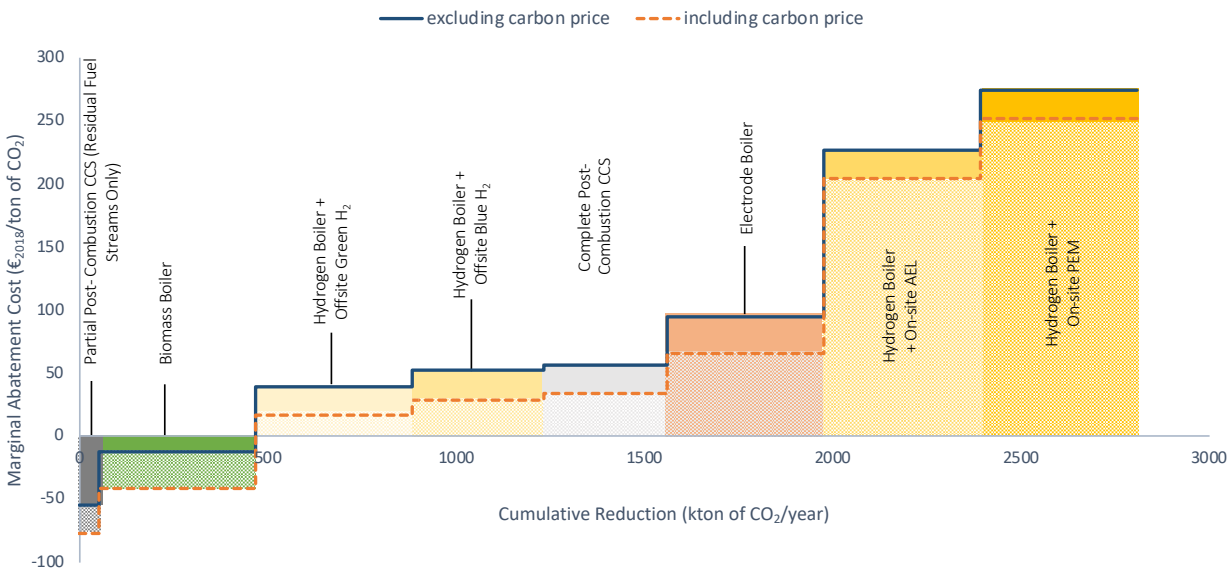

Figure 23: Figure showing the MAC curve for the Maasvlakte production site, following the WLO Low Scenario pricing trajectories. The orange dotted line and patterned bars refer to the marginal abatement cost considering the carbon price. The blue solid line and solid coloured bars refer to the marginal abatement cost without considering the carbon price.

The MAC results and technology ranking for Maasvlakte site are solely affected by the costs associated with the decarbonisation options, but not the reference situation[42]. The biomass boiler has risen in rank due to the lower biomass price. Partial CCS configuration remains the most cost-effective option with a slightly lower MAC. The option is unaffected by the higher natural gas price as no natural gas input is assumed but has benefited from the lowered wholesale electricity price. On the contrary, the complete CCS configuration and the Hydrogen Boiler + Blue H_2 options have become more expensive, due to the higher natural gas price.

[42] The reference situation assumes a constant steam purchasing price of 13 €$_{2018}$/GJ of steam.

Botlek Site

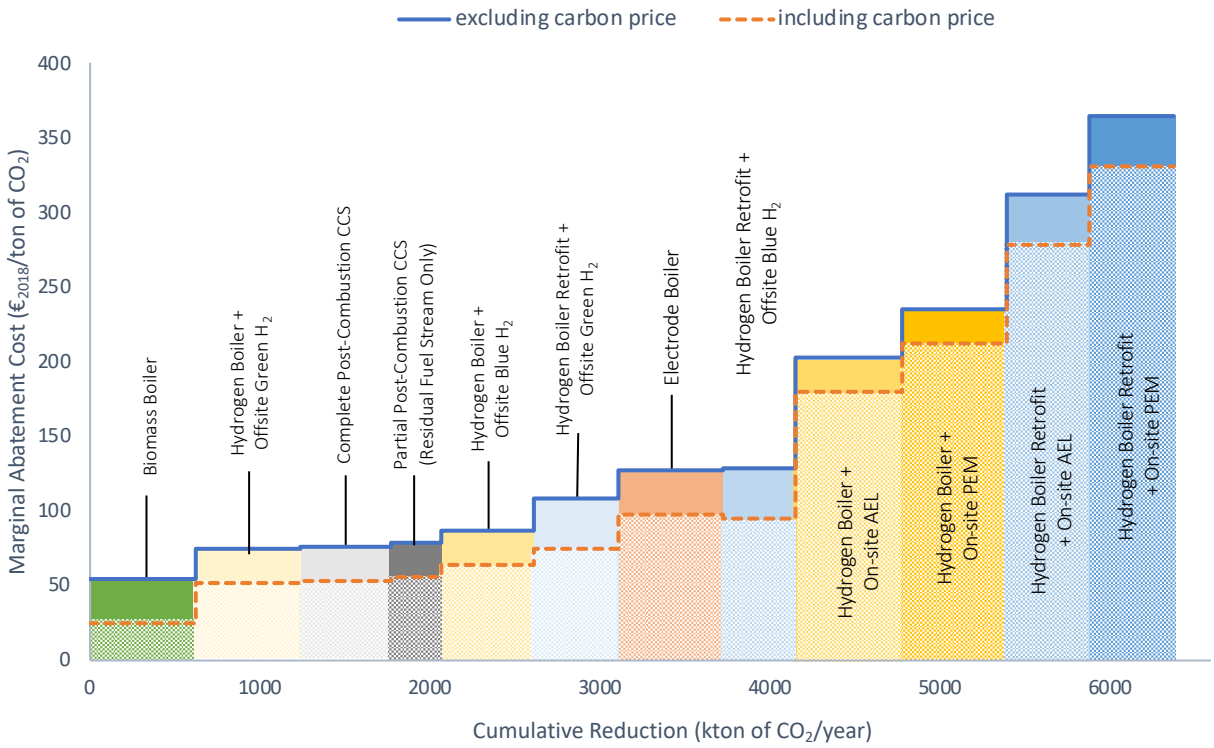

Figure 24: Figure showing the MAC curve for the Botlek production site, following the WLO Low Scenario pricing trajectories. The orange dotted line and patterned bars refer to the marginal abatement cost considering the carbon price. The blue solid line and solid coloured bars refer to the marginal abatement cost without considering the carbon price.

The increase in reference cost due to a higher natural gas price has contributed towards the lowering of MACs (excluding carbon price) of the decarbonisation options, except for the CCS technologies and the Hydrogen Boiler + Off-site Blue H_2. The options have instead become more expensive as a high amount of natural gas is required as fuel input.

It is noted that both the WLO High and Low scenarios fall short of 2°C commitment of the Paris agreement, as well as the currently stipulated EU and Dutch climate commitments. However as noted in [15], projected fuel prices for a 2-degree scenario are not readily available and uncertainty associated with the projected CO_2 prices rises drastically. The WLO High scenario prices are hence considered most suited for the MAC analysis in this research. Notwithstanding, fuel and carbon prices can be affected by other external factors not associated with global climate commitment. One apparent example is such as the current COVID-19 crisis which sees fossil fuel prices plunging to a record low.

7.1.6. AVERAGE ELECTRICITY GRID EMISSIONS & CERTIFICATE PRICE

The electricity emissions are assumed to be zero for the few technologies that utilise electricity as primary fuel input. These technologies are electrode boiler and the production of hydrogen using on-site Polymer Electrolyte Membrane (PEM) or Alkaline Electrolysis (AEL) technologies. However, the current and projected installed renewable electricity capacities have yet capable to substantially lower the average grid emissions. The average electricity grid emissions in 2030 are projected to be 187 kg/MWh. An analysis has been conducted to see what if the renewable electricity has not been specially procured for those technologies

as energy input. The following tables show the alternative results, using average grid emission factor of 187 kg/MWh in 2030, and assumed linear decrement to zero by 2050.

Table 32: MACs and the percentage of abatement for highly electricity-dependent options, assuming average electricity grid emission factor – Maasvlakte site

Technology	Percentage of Abatement	MAC; W/O Carbon Price ($€_{2018}/tCO_2$)	MAC ; with Carbon Price ($€_{2018}/tCO_2$)
Electrode Boiler	56%	254.0	199.5
Hydrogen Boiler + On-site AEL	53%	426.7	375.0
Hydrogen Boiler + On-site PEM	52%	502.6	450.9
Hydrogen Boiler Retrofit + On-site AEL	3%	8590.8	8521.0
Hydrogen Boiler Retrofit + On-site PEM	1%	37772.4	37652.0

Table 33: MACs and the percentage of abatement for highly electricity dependent options, assuming average electricity grid emission factor – Botlek site

Technology	Percentage of Abatement	MAC; W/O Carbon Price ($€_{2018}/tCO_2$)	MAC ; with Carbon Price ($€_{2018}/tCO_2$)
Electrode Boiler	36%	294.52	238.98
Hydrogen Boiler + On-site AEL	31%	789.09	738.08
Hydrogen Boiler + On-site PEM	29%	1010.77	959.88

As shown in Table 32 and Table 33, the grid emission factor assumed in the MAC curve analysis has a significant impact on the abatement potential, as well as the MACs of the decarbonisation options. Particularly, the hydrogen boiler retrofitting options for the Botlek production site provide a mere 1-3 % carbon abatement. This is due to the short lifetime assumed, corresponding to the early years where the average grid emission factor is high.

The sensitivity results emphasised the importance of green electricity in achieving decarbonisation through electrification options. While green electricity cannot be segregated or traced when fed into the national power grid, consumers may instead "green" their electricity supply by purchasing the Guarantee of Origin (GoO) certificates or through the arrangement of Power Purchasing Agreement (PPA), before the national power grid is fully decarbonised. One main criticism is that such practice may not contribute directly to the realisation of Dutch renewable energy projects unless local GoOs are purchased [97]. The additional price incurred is not included in the MAC curve analysis, as there is currently no transparent certificate market with majority arranged through bilateral agreements [98–99]. There is also a wide range of prices available, depending on the chosen energy sources and production locations. Particularly, GoOs produced within the Netherlands often have the highest price [99–100]. As a reference, the Dutch wind energy GoO price is 6.85 €/MWh in 2019. There is no clear future pricing development well into the MAC curve analysis period, though forecasted that the GoO certificate price may decrease in the long run, as the renewable energy supply increases [98–101]. The exclusion or inclusion of the additional certificate price in the MAC curve analysis does not affect the technology ranking in terms of cost-effectiveness, as the electricity-dependent technologies are the most expensive choice regardless.

7.2. LIMITATIONS OF THE MAC CURVES

The MAC curves shown in Chapter 6 generally give a good indication of the most cost-effective decarbonisation options, within LyondellBasell's context. The results may form the basis of further research, diving deeper into the practical implementation issues for the most promising technologies. Though ubiquitously used in many other contexts, including national policymaking, there are several limitations which are often associated with the MAC Curve methodology. The following addresses the limitations and how they might or might not limit the usefulness of the results presented in Chapter 6:

Intertemporal complexity: One major shortcoming of the MAC curve methodology is its failure to address the complex intertemporal issue in a simplistic curve [102]. The results in Chapter 6 presented a static snapshot of the MACs with 2029 as investment year (i.e. year 0), allowing carbon reduction from 2030 onwards. The MAC curve analysis conducted in this research acknowledged the temporal changes in fuel and carbon prices and their significance on the MACs by incorporating these variables as temporally dynamic variables. Meaning, the fuel and carbon prices assumed in the main analysis follow closely the pricing projections provided by the KEV 2019 [14] and the WLO High scenario [15]. Contrarily, utilisation of single point prices (i.e. fuel and carbon price in 2030 throughout the analysis period) shall fail to show the financial benefit offered by the increasingly high carbon price in the long run, as well as the influence of the projected changes in fuel prices. Nonetheless, the MAC results compare the different decarbonisation options based on their projected technological advancement and costs figures in 2030. This fails to illustrate how the possible technological advancement past 2030 may contribute towards the cost-effectiveness of the options in a single MAC curve. For example, it is expected that Polymer Electrolyte Membrane (PEM) or Alkaline Electrolysis (AEL) technologies may continue down their respective learning curves, improving on both the economic and technical aspects. Other decarbonisation options are relatively mature with which significant cost and technical improvements are not expected. However, the learning effect would possibly lower the MACs of PEM and AEL past 2030, though they are unlikely to reach cost parity with other mature technologies.

Path dependency: As quoted from [102], the MACs are path-dependent and sensitive to actions pre-dating the analysis period. The economic and technical parameters are collected based on publicly available sources, prioritising data that are most applicable to the Netherlands and reflect the possible technical and economic advancements for the year 2030. A selected number of parameters with higher data uncertainties are further analysed in 7.1. Notwithstanding, it should be noted that long-term data projections are in general uncertain and are dependent on the developments of earlier years. For example, the pricing trajectories, following the WLO scenarios, assumes the fulfilment of climate pledges in 2020. Additionally, the cost parameters of technologies such as AEL, PEM and hydrogen retrofitting options for 2030 can only be achieved if there are adequate research and development (R&D) effort and market implementation. The same goes for the cost of green hydrogen, which the lowering of production cost requires a widespread deployment of electrolysers worldwide.

Interactions between technologies: Another point of concern is that the MAC curves often lack the ability in presenting the interactions between technologies [102]. The MAC curves presented in Chapter 6 are fine examples of the shortcoming. The MAC curves consider primarily competing technologies and show the expected MACs of the options assuming 100% technology replacement. The exception is the partial post-combustion configuration, which considers part replacement of the reference technology. The partial post-combustion configuration allows the utilisation of residual fuel streams and may be combined with other technologies to achieve deeper decarbonisation. Other technological combinations may be considered, for example, electrode boiler + natural gas boiler. While useful in comparing the competing technologies, the

MAC curves presented in Figure 23 and Figure 24 are not able to capture the interactions between technologies. The interactions may lead to a different MAC and abatement potential of the decarbonisation options [102]. 7.2.1 explored the possibilities of combining the partial CCS configuration with other technologies and presented the overall MACs for the different combinations.

Non-economic factors: Lastly, the MAC curves provide a straight-forward comparison between decarbonisation options, based solely on their cost-effectiveness and their abatement potential. One criticism against MAC curves is that there is a lack of consideration of other non-economic factors. These are, for example, public opinions, policy constraints, supply scarcity, and technological maturity. These factors may create implementation barriers, resulting in cost-effective options not being implemented [103]. The non-economic factors relevant to the five most cost-effective options are further discussed in 7.3. Together with the results presented in Chapter 6 and the sensitivity analyses discussed in 7.1, the discussion shall allow conclusions to be drawn on the most appropriate technological choice(s), considering other non-economic factors.

7.2.1. PARTIAL CCS + OTHER TECHNOLOGY COMBINATIONS

As abovementioned, the MAC curves presented in Chapter 6 assumed a 100% technology replacement for all technologies, except for the partial CCS configuration. The following discusses the resultant MACs when the partial CCS configuration is implemented in combination with other decarbonisation options. To do so, the MACs for the individual decarbonisation options are first recalculated based on the reduced required capacity. Average MACs [43] are then calculated for the partial CCS configuration + other technology combinations and presented in the following figures. The results are also included in Table 48 and Table 49.

Maasvlakte

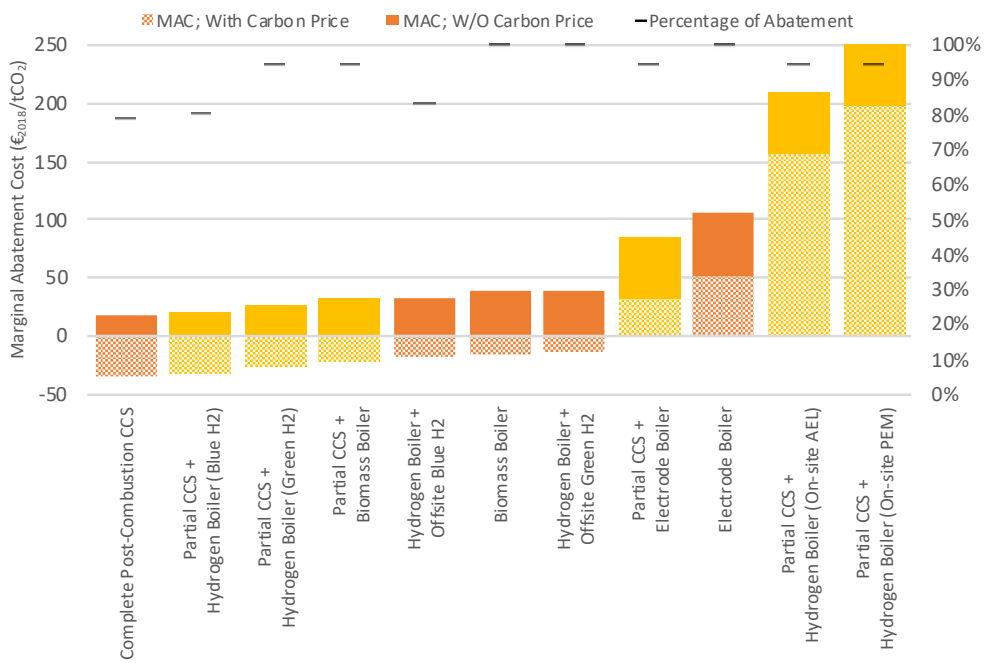

Figure 25: Figure shows the MACs of the different combinations (in yellow patterned or solid coloured bars) and the individual technologies (in orange patterned or solid coloured bars; assuming 100% replacement) for the Maasvlakte site. The patterned bars correspond to the MACs with carbon price, while the solid-coloured bars correspond to the MACs without carbon price.

[43] The average MACs are calculated using the formula $\frac{MAC_{CCS} \times \Delta CO2_{CCS} + MAC_T \times \Delta CO2_T}{\Delta CO2_{CCS} + \Delta CO2_T}$, where CCS refers to the partial CCS configuration and T refers to the other decarbonisation options. The MACs of these combinations are calculated based on one single life cycle per technology.

The MACs of the decarbonisation options are generally unaffected at a reduced required capacity. However, the highly negative MAC of the Partial CCS configuration (13% abatement potential) allows a low overall MAC for all the technology combinations (i.e. Partial CCS + Hydrogen Boiler (Blue H_2)), in comparison to their respective individual options (i.e. Hydrogen Boiler + Blue H_2). The disadvantage is that the technological combination does not allow a 100% abatement, due to the carbon-capturing efficiency of 90%. The cheapest option offering deep decarbonisation is still the Complete Post-Combustion CCS option, at 79% abatement.

Botlek

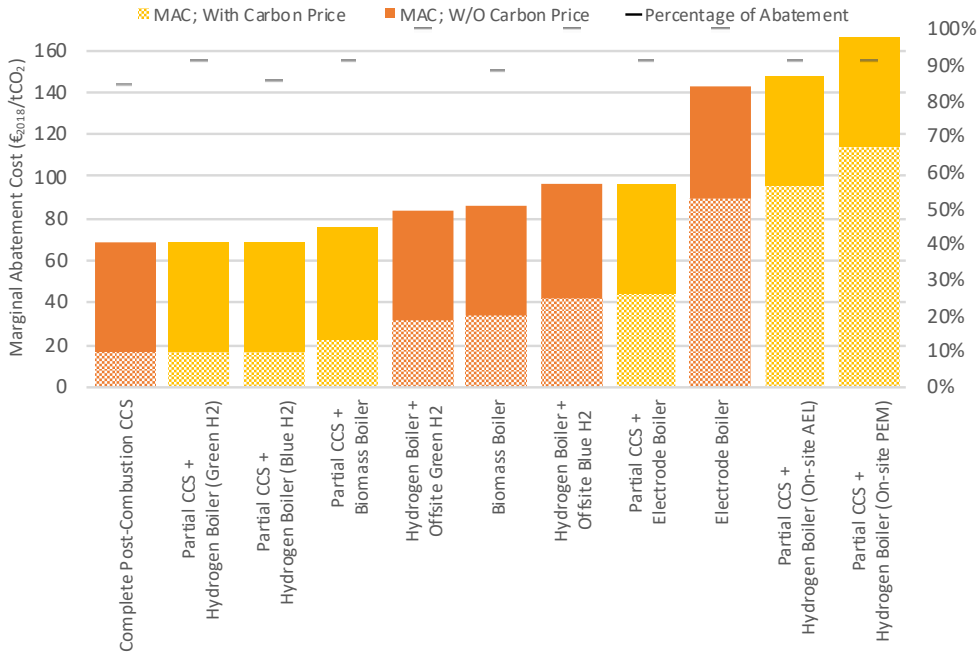

Figure 26: Figure shows the MACs of the different combinations (in yellow patterned or solid coloured bars) and the individual technologies (in orange patterned or solid coloured bars; assuming 100% replacement) for the Botlek site. The patterned bars correspond to the MACs with the carbon price, while the solid-coloured bar correspond to the MACs without the carbon price.

The MACs of the decarbonisation options at a reduced required capacity has increased or decreased, depending on the options. Similarly, a reduced overall MAC is achieved in combination with the partial CCS configuration, in comparison to their respective individual options. The cheapest option at deep decarbonisation is still the Complete Post-Combustion CCS, followed closely by Partial CCS + Hydrogen Boiler (Green H_2) and Partial CCS + Hydrogen Boiler (Blue H_2) combinations.

7.3. QUALITATIVE DISCUSSION ON THE NON-ECONOMIC FACTORS

The following discusses the top five decarbonisation options[44], ranked according to their cost-effectiveness (see Chapter 6), concerning the relevant non-economic factors that might impact the implementation of the decarbonisation options. The discussion below is however non-exhaustive and based mainly external factors. Additional implementation barriers relevant to LyondellBasell may exist, i.e. operational constraints.

[44] The decarbonisation options are Partial Post-Combustion CCS, Complete Post-Combustion CCS, Hydrogen Boiler + Blue H_2, Hydrogen Boiler + Green H_2 and Biomass Boiler. These options are generally at a close competition, in terms of cost-effectiveness, though the ranking is slightly different for Maasvlakte and Botlek sites. Other decarbonisation options are not further discussed qualitatively as their MACs are substantially higher.

Unfortunately, the lack of input from LyondellBasell hinders the following discussion at a finer, more specific detailedness.

Post-Combustion CCS options, including the Partial (residual fuel streams only) and the Complete CCS configurations, are ranked the top two options, in terms of cost-effectiveness. CCS generally receive opposing public opinions on its role in driving the sustainable energy transition. A research conducted by [104] shows that CCS garnered the least support in the Netherlands, among four other surveyed countries. Major concerns include long-term storage risks, as well as it encourages the prolonged use of fossil fuels. In the case of LyondellBasell, the use of CCS shall sustain LyondellBasell's dependency on fossil fuel (i.e. natural gas) at least past 2050. On the policy front, the European Union [105] and the Netherlands recognise the significant potential of CCS in achieving climate reduction goals. While onshore CCS projects are banned within the Netherlands, following the case of Barendrecht project [106], offshore CCS and CCU (carbon capture and utilisation) projects are allowed and are actively pursued. For example, various subsidy schemes are provided by the Netherlands Enterprise Agency (RVO) [107]. Notwithstanding, the decarbonisation options require large scale, preferably collective infrastructure, as offered by PORTHOS project. In the case of the PORTHOS project, it has recently been granted the Project of Common Interest (PCI) status by the European Union, as part of the umbrella project - CO2 TransPorts[45]. The PCI status allows potential EU subsidy to be granted to the PORTHOS project [108]. Such policy support has enhanced the implementation feasibility of the options. Nonetheless, the CCS options do not offer a complete carbon abatement, hence requiring additional intervention(s) in meeting the ambitious 2050 reduction goal. For example, biomass (i.e. biogas) may be co-fired to reach net-zero emissions or even negative emissions.

The hydrogen combustion options, specifically with the use of blue H_2 and green H_2, are at a close competition, in terms of cost-effectiveness. The blue H_2 production requires the use of CCS and natural gas, hence arguments against the CCS options are also relevant. The supply of green H_2 is however insecure in the 2030s. The upscaling of green hydrogen production requires a much bigger penetration of renewables (i.e. wind and solar), which is currently not available. A more realistic timeline may be between 2040 - 2050, where the production cost has reached cost parity with blue H_2 and when more renewable electricity is readily available. LyondellBasell could make use of Port of Rotterdam's ambition in transforming into a regional hydrogen hub [109]. The Port of Rotterdam plans to be connected to a total of 18 – 24 GW Dutch offshore wind for green hydrogen production in the 2040s. It also plans to import hydrogen from world regions with abundant green hydrogen potential to serve its domestic and regional customers. On the other hand, the Blue H_2 production through the H-Vision is envisioned to start its first supply in 2026. The H-Vision project also involves the construction of a common H_2 distribution network, which shall facilitate the distribution of green H_2 in the long run. It is important to note that decarbonisation can only be realised through hydrogen combustion if blue H_2 or green H_2 is used. Similar to the CCS options, the supply security of blue or green H_2 is enhanced when there is a collective infrastructure effort (as offered by H-vision project) or an established trading hub and distribution network. Alternatively, self-production may be established (i.e. on-site AEL or PEM) at a much greater cost.

Biomass Boiler option is comparatively attractive, particularly in the WLO Low scenario. The domestically sourced biomass is currently at a lower price than imported biomass, though it is expected that increasing amount of wood chips and pellets have to be imported meet the biomass demand [87]. Owing to LyondellBasell's strategic location in the Port of Rotterdam, the supply of woody biomass may be facilitated through the Port of Rotterdam. The Port of Rotterdam has a good shipping connection to Canada and the United States, the two main wood pellet suppliers. It also has extensive biomass handling facilities, making

[45] The CO2 TransPorts project aims to connect the neighbouring ports (i.e. Antwerp, Ghent) to the PORTHOS storage field, via CO_2 pipeline.

it an attractive biomass hub for the Northwestern Europe market [110]. It is recognised that biomass plays a major role in a climate-neutral economy. Nonetheless, the use of biomass, particularly for energetic purpose is highly controversial. As of now, the co-firing of biomass in coal-fired power plants is kept at 25PJ annually [111]. On the other hand, biomass for renewable heat and CHP may be eligible for the Stimulation of Sustainable Energy Production (SDE+) scheme, if the sustainability criteria are met [112]. The SER has recently called for the subsidy to be phased out for electricity and low-temperature applications, while high-temperature heat generation with fewer alternatives may be given the priorities [113]. However, the availability of sustainable biomass is likely to be a constraint in the long run. It is expected that the possible biomass demand of the Netherlands cannot be fulfilled by the local supply and are substantially high, relative to the global and EU availability. Other negative arguments provided in a recent report by PBL [114] include the long carbon payback time and the potential abuse of the wood pellet industry. It is also suggested that there shall be a cascaded and efficient use of biomass, with direct combustion of biomass being the least preferred usage. With these being said, the use of biomass for high-temperature steam generation may be a riskier option, running into supply security issues and possibly a restricted use for energetic purposes, in the future.

7.4. RESIDUAL FUEL STREAMS AND THEIR ASSOCIATED EMISSIONS

Residual fuel streams are unavoidable for the chemical processes at LyondellBasell, and the amount is significant (see Table 35 and Table 37). The fuel streams are currently utilised on-site or sent to external utility companies as replacement fuels. Notwithstanding, the fuel streams is an important source of carbon emissions if unmitigated. On the other hand, the replacement of boilers fuelled by residual fuel streams by other technologies (i.e. hydrogen boiler, electrode boiler), particularly for the Botlek site, would lead to a surplus of residual fuel streams. Alternative usage of the fuel streams shall be sought conscientiously. The following proposes several measures in mitigating the emissions associated with the residual fuel streams.

The residual fuel streams may continue to be utilised for steam generation purposes, with carbon emissions reduced through post-combustion CCS. If the partial CCS configuration is implemented, the remaining steam demand may be supplemented by other technology of choice. These are analysed and presented in Chapter 6 and 7.2.1. Alternatively, the residual fuel gas streams can be used in blue hydrogen production. As proposed by the H-Vision project, the residual fuel gas streams will be converted into syngas through auto thermal reforming (ATR). The resultant CO_2 stream will be captured and stored/reutilised.

Otherwise, the emissions from the residual fuel streams may be avoided or reduced through the use of bio-based feedstock in the chemical processes. The subsequent combustion of the residual fuel streams can then result in reduced or zero (scope 1) emissions, depending on the percentage of bio-based input and if the sustainability standards set out by the EU Directive is met. This option is not investigated further as it is not part of the research scope. However, the possible concerns are the sufficient supply of sustainable bio-based feedstock, as well as the scope 3 emissions associated with the upstream feedstock production. Lastly but not ideally, the residual fuel streams may be sent to other parties. This effectively reduces scope 1 emissions due to the combustion of residual fuel streams. However, depending on the decarbonisation measures taken by the external parties, such measure may increase the scope 3 emissions, hence carbon emissions to the atmosphere overall.

7.5. OTHER LIMITATIONS OF THIS RESEARCH

Several uncertainties and limitations of the MAC curve results have been addressed and discussed in the previous subchapters. For example, Subchapter 7.1 addresses the uncertainties associated with several cost and technical assumptions. The limitations of the MAC curves in supporting decision-making were discussed in 7.2, complemented by quantitative and qualitative discussions, such as on the non-economic factors. Nonetheless, there are a few additional limitations of this research, mainly linked to the limited research scope and the lack of specific data input from LyondellBasell.

One major limitation is with regard to the uncertainties associated with the current process data. As previously mentioned, this research was unable to seek input or verification from LyondellBasell, due to legal confidentiality reasons. All current process information was collected from public resources. The data uncertainties are particularly high for the processes with multiple possible process configurations, i.e. MTBE/ETBE production and butane isomerisation process. Additionally, assumptions were made for the total amount of electricity and steam consumption. Specifically, deriving the amount of steam consumption from the EU-ETS carbon certificate free allocation. Hence, the energy consumption determined in this research may not reflect the actual energy usage. Other assumptions include the reference technologies used in steam generation and their efficiencies, as well as the primary fuel input These assumptions have an important implication on the MAC curve results. As an example, a more carbon-intensive fuel input (such as coal), hence a higher-than-assumed emission factors of the steam supply, would result in increased abatement potential and decreased MACs of the decarbonisation options. Nonetheless, the impact on the technology ranking presented in Chapter 6 is not expected to be significant.

Secondly, this research focuses on a limited number of drop-in, commercially available decarbonisation options, specifically for the decarbonisation of steam supply. Process-specific or heat integration measures have not been investigated, mainly due to the lack of fine technical details about the process and plant configurations. Notwithstanding, there might be process-specific measures that may be more appropriate to be implemented first, before pursuing the analysed options. The research scope also assumes LyondellBasell's independent effort in decarbonising its scope 1 and 2 steam-related emissions. This is a logical assumption for the Botlek site, as the production site is in theory capable of covering its steam requirements. The main uncertainty lies with the Maasvlakte site, as the production site is solely dependent on the external steam supply (i.e. UCML and MPP3). Collective decisions between LyondellBasell and the external providers, particularly the new MPP3 plant, may potentially be sought. Further clarification on such matter has not been provided by LyondellBasell. Besides, the high-level assessment performed in this research fails to address the possible technical implementation and operational barriers.

Lastly, this research scope addresses only scope 1 and 2 emissions, specifically steam-related emissions. Due to time-constraint, decarbonisation opportunities, such as using recycled feedstock etc., in reducing LyondellBasell's scope 3 emissions are not further investigated. Notwithstanding, a simultaneous reduction in scope 3 emissions throughout its product value chain, starting from feedstock production to end-of-life management, would have a significant implication for the overall carbon mitigation. Particularly, the feedstock production is energy intensive, making up about 70% of the total energy consumption throughout the value chain [27].

7.6. RESEARCH IMPLICATIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

7.6.1. RESEARCH IMPLICATIONS

The main objective of this research is to contribute towards the MIDDEN database, by providing an open-source plant- and process- knowledge for the stakeholders and the general public. The MIDDEN database, as a whole, would provide better transparency on the Dutch industry, serving as a foundation for further research and aid decision-making. While not necessitated by the MIDDEN project, the MAC curve analysis and discussion conducted in this research provide a better picture of the most probable decarbonisation option(s), in terms of both cost-effectiveness and implementation feasibility. This research has also explored the effect of the carbon price, as well as the different pricing trajectories resultant from varying degree of global climate commitment, may have on the cost-effectiveness of the options. This, hopefully, shed some light for the policymaking, from a bottom-up perspective.

The decarbonisation measures analysed in this research are cross-company/cross-sectoral applications. Meaning, they are suitable for companies or industries with a high reliant on high-temperature steam. While the MAC curve results may have limited direct implications for other companies/sectors, as the results are sensitive to the reference technologies replaced and the baseline emissions assumed, it is hoped that the general technology ranking and discussions may serve as informational guidance on the most promising options. Specifically, for companies or industries that are placed in locations that are strategically similar to the Port of Rotterdam, with a possible connection to a CCS storage site and supply of blue/green hydrogen.

7.6.2. RECOMMENDATIONS FOR FURTHER RESEARCH

The abovementioned limitations may serve as a lead for further research. Firstly, further research may build on the results presented in this research to conduct in-depth technical assessments on the most promising options, i.e. CCS. The technical assessments may touch upon factors such as spatial constraints, operational complexity and safety risks. The opportunities to integrate biomass co-firing with the CCS options may be explored, allowing net-zero or negative emissions. If not, further research may expand on the non-exhaustive list of analysed decarbonisation options, such as by considering process-specific energy efficiency measures, if sufficient technical details are available, or other technological combinations (i.e. hybrid gas and electrode boiler). Alternative research focus can be on the decarbonisation opportunities of scope 3 emissions and the use of recycled/bio-based feedstock, which together with this research, consider carbon mitigation throughout the value chain.

The limitations of MAC curves are widely criticised, such as its inability to address the non-economic factors. Future research may improve on such limitations by employing a different assessment methodology. One example is the Y-factor method, put forward by [115]. The Y-factor method provides a quantitative method to internalise the non-economic factors by assigning scores to 13 factors and presenting the overall results in a way similar to the conventional MAC curve. Such comprehensive quantitative insights shall allow better comparisons between the decarbonisation options.

CHAPTER 8: CONCLUSION

This research set out to propose the most appropriate decarbonisation option(s) in decarbonising LyondellBasell's operations at Botlek and Maasvlakte, at the reference year of 2030. To achieve the main and sub- research objectives, a thorough understanding of its current operations is first gathered from public sources to inform the scope 1 and 2 emission hotspots, subsequently prioritising the most promising decarbonisation options. The marginal abatement cost (MAC) curve analysis, allowed comparisons to be done between the decarbonisation options, in terms of the cost-effectiveness. Subsequently, the five most cost-effective options are further discussed qualitatively with regards to the relevant non-economic factors, providing a comprehensive view of their implementation feasibility. Following the research, it can be concluded that **the post-combustion CCS (complete configuration) and hydrogen boiler + Off-site Blue H_2 options have better advantages in terms of both cost-effectiveness and implementation feasibility in achieving deep decarbonisation.** The following provides the outcomes addressing the research sub-objectives.

LyondellBasell's has a diverse product portfolio, produced through six main chemical processes in its production site in Botlek and one main process in Maasvlakte. Its plant-wide integration allows optimised product flows across production processes and operating sites, as well as cascaded steam usage across process units. The integration between the production sites and the neighbouring utility companies also makes scope 2 emissions an important source of emissions. The overall steam consumption for the production sites is significant, amounting to around 8 PJ for both sites. This, in turn, has resulted in a substantial amount of emissions, **making up around 88% of the total scope 1 and 2 emissions** – or in absolute term, an annual amount of 416 and 620 kton of CO_2, for Maasvlakte and Botlek sites respectively. Accordingly, in consideration of the other selection constraints, this research prioritised the decarbonisation of steam supply.

The seven decarbonisation options analysed in this research include post-combustion CCS of two different configurations, hydrogen combustion options in combination with four different hydrogen sources, biomass boiler and electrode boiler. The MAC curve analysis yielded different results for the Botlek and Maasvlakte sites, as the reference situations considered, i.e. reference technologies and baseline emissions, are different. Nevertheless, a few general conclusions can be drawn from the main results, assuming pricing trajectories reaching the 2050 prices provided by WLO High scenario. The results show that climate-positive technologies can hardly compete with the current carbon-intensive status quo, without the presence of a substantially high carbon price. An increasing carbon price trajectory, reaching a carbon price of 169 $€_{2018}/tCO_2$ in 2050, improves the cost-effectiveness of the options by around 52 $€_{2018}$/ton of abated CO_2. Secondly, the expected increase in average grid electricity price to around 105 $€_{2018}$/MWh makes the electricity-dependent technologies unattractive, particularly hydrogen production through on-site alkaline electrolysis (AEL) and Polymer Electrolyte Membrane (PEM) technologies of low conversion efficiencies. **The technology ranking, in terms of cost-effectiveness, in both production sites is led by the CCS technologies**, of which the complete CCS configuration allows deep decarbonisation at an abatement cost of -33.6 $€_{2018}/tCO_2$ for Maasvlakte site (79% carbon reduction) and 16.4 $€_{2018}/tCO_2$ for Botlek site (85% carbon reduction), considering the carbon price. This is followed closely by hydrogen combustion options with blue hydrogen and green hydrogen, and biomass boiler.

The sensitivity analyses on a number of parameters and the qualitative discussion with regard to the relevant non-economic factors further affirm that Complete Post-Combustion CCS configuration may be one of the

most appropriate decarbonisation options, for both production sites in achieving deep decarbonisation. One concern with the CCS option is the fossil fuel lock-in effect, prolonging LyondellBasell's dependency on fossil fuels past 2050. **Hydrogen Boiler + Off-Site Blue H_2 option is also promising, though has a higher MAC.** The option has an abatement cost of -18.8 $€_{2018}/tCO_2$ for the Maasvlakte site (84% carbon reduction) and 33.6 $€_{2018}/tCO_2$ for the Botlek site (88% carbon reduction), considering the carbon price. A technological combination of Hydrogen Boiler + Off-site Blue H_2 and partial CCS for residual fuel streams may also be considered. This allows the utilisation of the residual fuel streams, at the same time, providing cost-incentive. One major uncertainty for both options is the CCS processing tariff, of which biomass boiler and Hydrogen boiler + Offsite Green H_2, are favoured at high CCS processing tariff. Additionally, the fuel pricing trajectories has a significant impact on the technology ranking, which saw the biomass boiler option as the most cost-effective option in the WLO Low scenario. However, due to the possible supply scarcity and the sustainability issues, biomass may not be a reasonable zero-carbon alternative. On the other hand, it is not expected that there would be a secure supply for green H_2, not until a green H_2 trading hub or a good integration with renewable electricity supply is established. Notwithstanding, the implementation of hydrogen combustion with blue H_2 shall facilitate a smooth transition into green H_2 application as a fuel supply.

To conclude, the complete Post-Combustion CCS configuration and Hydrogen boiler + Offsite Blue H_2 may be the most-appropriate decarbonisation options for deep decarbonisation, considering both the cost-effectiveness and the overall implementation feasibility. This conclusion also aligns well with the initiatives currently put forward for the Port of Rotterdam industrial cluster, the PORTHOS and the H-vision projects. It is, however, important to reiterate the limitations of this research, such as the path dependency of the MAC curve results and the uncertainties with regards to the assumed steam consumption and baseline emissions. These may have an effect on the MACs, but less likely on the conclusion. Additionally, further research in addressing technical implementation and operational barriers is imperative in drawing the final investment decision.

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APPENDICES

A.1. CURRENT PROCESSES AT THE MAASVLAKTE SITE

INPUT MATERIALS

Table 34 shows an estimation of the annual material consumption for the PO/SM co-production process, including the benzene alkylation process. The figures are estimated based on the SM production capacity of 864 kton and the material consumption values (on per unit tonne of product basis) indicated in Table 4 and Table 5.

Table 34: Annual material input for the PO/SM co-production process

Input Material	Annual Input (kton/year)
Benzene	734.3
Ethylene	263.3
Propylene	284.2
Hydrogen	3.6

RESIDUAL FUEL STREAMS

The amount of waste streams is estimated based on the statistics provided for 2006 in [29] and the (expected) increased in the original production capacity by 35% [24]. The waste fuel streams (with the exception of RFO-637) are used as on-site replacement fuels for the suggested decarbonisation options of complete and partial post-combustion CCS configuration. The RFO-637 stream is used as combustible fuel streams for wastewater incineration in AVR Rozenburg.

Table 35: Estimated amount of waste fuel streams from Maasvlakte site

	Annual amount (ton/year)	Energy Content (PJ/year)
Propane	8000	0.36
Glycolic Fuel	12000	0.49
Heavy Liquid Fuel (RFO-635)	30100	1.23
Fuel Gas	10500	0.48
Other Combustible Stream (RFO-637)	40300	-

EXTERNAL UTILITY COMPANIES

UCML was established in 2003 and consists of a gas-fired CHP (gas turbine equipped with a heat recovery steam generator (HRSG)) and direct-fired boilers [116–117]. It was primarily set up to produce processing steam for LyondellBasell's Maasvlakte site and is connected to Maasvlakte site through a 25kV electricity cable [118]. Rated at 70 MW electricity output and 375ton/hour steam output [119], UCML also provides utilities to NesteOil and LNG GATE Terminal [120]. MPP3, recently commissioned in 2017, is a coal and biomass (maximum of 30%) co-combustion power plant rated at 1070 MW. Besides, the new plant also produces steam and cooling water for nearby businesses, including LyondellBasell [30–121].

A.2. CURRENT PROCESSES AT THE BOTLEK SITE

INPUT MATERIALS

Table 36 shows an estimation of the annual material consumption for the different processes in the Botlek production site. The figures are estimated based on the production capacities listed in Table 3 and the material consumption values (on per unit tonne of product basis) indicated in their respective material and energy balance tables.

Table 36: Yearly material consumption (kton/year) for the different processes at the Botlek production site

Input Material	Process	Annual Input (kton/year)
Propylene	PO/TBA co-production	181.1
	Total	**181.1**
Mixed Butane	PO/TBA co-production	511.4
	Total	**511.4**
Oxygen	PO/TBA co-production	196.6
	Total	**196.6**
Propylene Oxide (PO)	Production of PG	88.0
	Production of PGME	68.2
	Production of BDO, allyl alcohol, MPD	83.7
	Total	**239.9**
Methanol	Production of PGME	37.6
	Production of MTBE/ETBE*	145.4
	Total	**183.0**
TBA	Production of isobutylene	142.6
	Total	**142.6**
Isobutylene	Production of MTBE/ETBE	258.5
	Total	**258.5**
Carbon Monoxide (CO)**	Production of BDO, allyl alcohol, MPD	37.3
	Total	**37.3**
Hydrogen (H_2)**	Production of BDO, allyl alcohol, MPD	5.3
	Total:	**5.3**

**assumed production of MTBE only*

***material consumption approximated based on the production capacities of both BDO and MPD*

RESIDUAL FUEL STREAMS

Table 37: Estimated amount of waste fuel streams – Botlek site

	Annual amount (ton/year)	Energy Content (PJ)
A fuel	38500	1.58
Fuel gas	20300	0.92
Pentane	6800	0.31
Propane	7100	0.32
Others	43500	1.87

ENERGY CONSUMPTION OF THE INDIVIDUAL PROCESSES

The energy consumption figures are estimated based on the annual production capacities (see Table 3) and the products' energy intensities, indicated in their respective mass and energy flows tables.

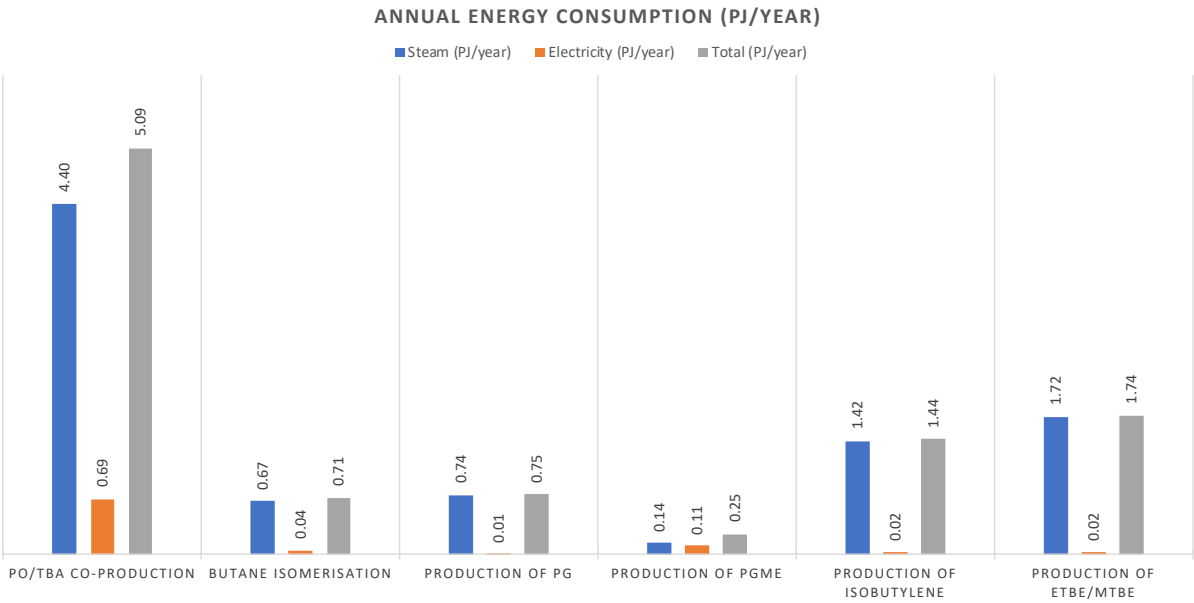

Figure 27: Annual energy consumption for the individual processes at the Botlek site

EXTERNAL UTILITY COMPANIES

WKC Air Products is a combined-cycle gas turbine (CCGT) combined heat and power (CHP) plant co-owned by Air Products and Electrabel. It is rated at 96 MW_{elec} and 225 tonnes of steam output per hour [23–122]. The CHP plant supplies steam to LyondellBasell, while the produced electricity is self-consumed by Air Products and sold to the electricity grid [123]. In addition, LyondellBasell is supplied with steam and electricity from Eurogen C.V. Rotterdam Rozenburg. It is a CHP facility consisting of two gas-fired plants co-owned by Huntsman, LyondellBasell, ENECO and Air Liquide; and has an electricity and steam capacity of 88 MW_{elec} and 270 tonnes of output per hour [124]. The external utility facilities also receive the waste fuel streams produced by LyondellBasell Botlek [27].

ANNUAL STEAM-RELATED EMISSIONS

The annual steam-related emissions are calculated based on a so-called "self-sufficient scenario". This scenario also serves as the reference situation, while the emissions serve as the baseline emissions for the MAC analysis. The self-sufficient scenario assumes that all waste fuel streams identified in Table 37 are utilised on-site, with the remaining fuel input supplemented by natural gas.

The steam output is calculated based on the boiler efficiencies indicated in Table 40, while the emission factors are as listed in Table 42.

Table 38: Steam output by fuel type and their respective emissions.

	Steam Output (PJ)	Emissions (kton)
A fuel	1.33	122.2
Fuel gas	0.69	57.3
Pentane	0.23	19.2
Propane	0.24	20.0
Others	1.49	131.0
Natural Gas	4.06	270.7
Total	**8.04**	**620.3**

A.3. DECARBONISATION OPTIONS

HYDROGEN PRODUCTION

Hydrogen can be produced from fossil-based (i.e. natural gas, coal) and renewable-based (i.e. biomass, renewable electricity) energy, through a wide variety of production routes. Hydrogen produced from fossil-based and biomass feedstock generally involves a thermal conversion route to produce syngas (carbon monoxide and hydrogen). A biochemical conversion route can also be applied on biobased feedstock (i.e. liquid fuels, biogas). Power-to-hydrogen technologies involve the use of electricity allows the production of hydrogen through electrolysis. The three categories of hydrogen, differing in terms of decarbonisation potential, are as summarised below:

- **Grey hydrogen:** Grey hydrogen production involves the production of hydrogen from fossil-fuel-based carbon carriers without the use of CCS. This hence entails the release of CO_2 into the atmosphere. This is the most prevalent form of hydrogen on the current market. The commonly applied production route is the steam methane reforming (SMR) of natural gas. Other thermochemical routes may also be applied, for example, the auto thermal reforming (ATR) and gasification of solid fuels [125].
- **Blue hydrogen:** Blue hydrogen is generally produced through the same way as the grey hydrogen but involves the use of CCS [125]. The carbon reduction potential is significant, depending on the production routes.
- **Green hydrogen:** Green hydrogen refers to hydrogen production from renewable-based primary energy sources. This can be, for example, using electricity from renewable energy sources in the water electrolysis process. The most common electrolysis technologies are the alkaline water (AEL) and the polymer electrolyte membrane (PEM) electrolysis [125]. A list of eleven green hydrogen

production pathways has also been suggested by [126], using solar thermal energy, sunlight or biomass as the major energy input.

Figure 28 shows the projected levelised cost of green hydrogen between 2020 – 2050 [79]

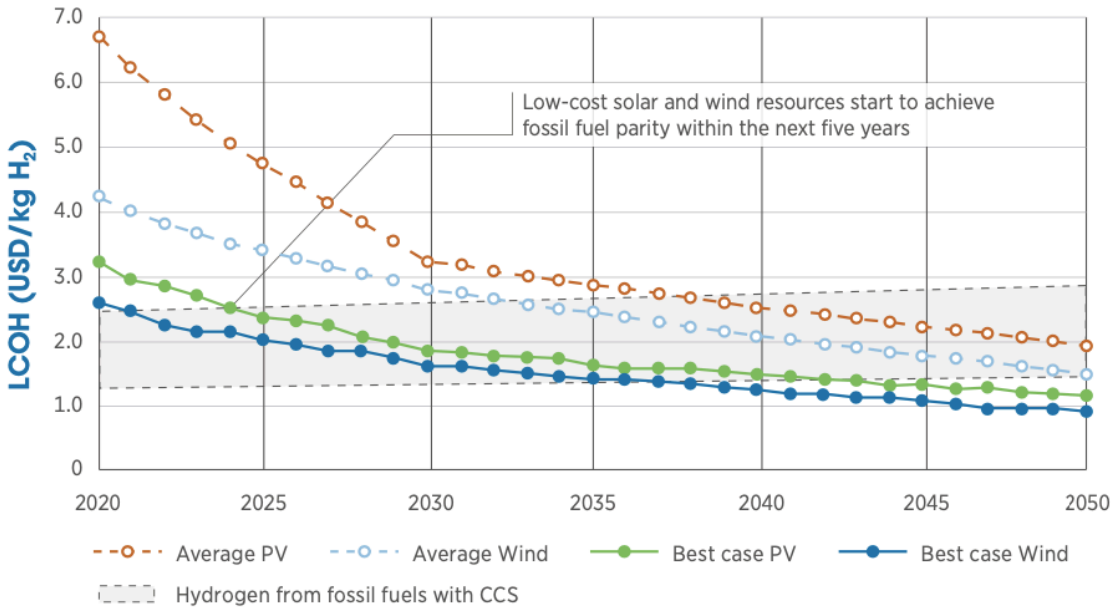

Figure 28: Projected levelised cost of green hydrogen between 2020 – 2050 [79]

CARBON CAPTURE AND STORAGE (CCS)

Carbon capture technologies may be differentiated into three broad categories:

Post Combustion: Carbon capture takes place after fuel combustion in a post-combustion process, removing CO_2 from the flue gas [90].

Pre-combustion: Primary fuel (i.e. coal, natural gas) is first converted into H_2 and CO_2 through processes such as gasification and steam reforming. The pure stream of CO_2 is then captured [90]. A practical example is such as the H-Vision blue hydrogen project.

Oxyfuel Combustion: Oxygen, instead of air, is used in the oxyfuel combustion process. This results in flue gas stream composed mainly of CO_2, water, particulates and SO_2. The particulates and SO_2 is separated out through conventional methods, while the pure stream of CO_2 is captured and stored. The technology however requires a large amount of oxygen from the energy-intensive air separation units [90]. Adjustments are also required for the existing air-fired boilers, including the installation of specific burners, flue gas recycling duct and fan [127].

PARTIAL CCS OF RESIDUAL FUEL STREAMS

The following details on how partial CCS of residual fuel streams are considered and analysed in the MAC curve analysis:

Maasvlakte

The residual fuel streams listed in Table 35, with the exception of RFO-637, are reutilised on-site using steam boilers. The regenerative heat required for the CCS operation is provided for by the steam generated by the fuel streams. This results in a net useful steam output of 1.41PJ.

The 90% capture efficiency results in a total emission of 18.5 kton of CO_2/year. The avoided carbon emissions are 55.7 kton/year, in comparison to the reference emissions of 74 kton/year from a gas-fired CHP, producing steam output of 1.41PJ.

Botlek

The amount of steam output from the residual fuel streams (listed in Table 37) in the reference situation is estimated to be 3.98 PJ. A reduced useful output of 2.72 PJ from the fuel streams is expected in a partial CCS configuration as heat is required for the regeneration of the MEA sorbent. The steam output reduction is compensated by the use of natural gas of around 1.95 PJ.

The 90% capture efficiency results in a total emission of 46 kton of CO_2/year. The avoided carbon emissions are 304 kton/year, in comparison to the reference emissions of 350/year kton resulted from the combustion of residual fuel streams without CCS.

PARAMETERS FOR FOSSIL FUEL-BASED STEAM BOILERS

Table 39: Technical and economic parameters for a natural gas fired-steam boiler

Parameter	Unit	Value	References
Technical Lifetime		25	[128]
Investment Cost *Reference capacity: 115 MW*	€$_{2018}$/kW$_{th}$	28	[128]
Fixed O&M Cost	€$_{2018}$/kW$_{th}$/year	1.96	[128]
Variable O&M Cost	€$_{2018}$/MWh/year	1.0	[128]
Fuel Cost		natural gas price (see A.4)	

Table 40: Reference efficiency values for steam generation by fuel type

Fuel Type	Steam Boiler Efficiency	References
Natural Gas, LPG, LNG	85%	[129]
Heavy Fuel Oil	84%	[129]
Recovered Gas	75%	[129]

A.4. OTHER PARAMETERS & RELEVANT FORMULAS

LOWER HEATING VALUE (LHV) AND EMISSION FACTOR BY FUEL TYPE

Table 41: Lower heating value (LHV) by fuel type

Fuel type	Unit	Value	References
Natural Gas	GJ/Nm^3	0.03165	[130]
Residual Fuel Oil *(e.g. A fuel, glycolic fuel, heavy liquid fuel streams)*	GJ/ton	41	[130]
Chemical Waste Gas *(e.g. propane, pentane and fuel gas streams)*	GJ/ton	45.2	[130]
Wood Pellets	GJ/ton	17	[86]
Hydrogen	GJ/ton	120	[131]

Table 42: Emission factors by fuel type

Fuel	Unit	Value	Reference
Natural Gas	kg/GJ	56.6	[130]
Residual Fuel Oil *(e.g. A fuel, glycolic fuel, heavy liquid fuel streams)*	kg/GJ	77.4	[130]
Waste Chemical Gas *(e.g. propane, pentane and fuel gas streams)*	kg/GJ	62.4	[130]
Average Electricity Grid Emission (2030)	kg/MWh	187	[72]
Biomass	kg/GJ	0	[28]
Green Hydrogen (Off-site)	kg/GJ	0	-
Blue Hydrogen (H-Vision)	ton/MWh	0.028	[76]

FUEL AND CARBON PRICE ASSUMPTIONS

Table 43 summarises the price assumptions used in the MAC curve analysis. With the exception of wholesale steam and oxygen, the 2025 and 2030 reference prices are based on [14], while the 2050 prices are based on the WLO scenarios in [15]. The prices between and beyond the reference points are linearly interpolated and extrapolated. The main results assumed trajectories reaching the 2050 prices provided by WLO High scenario, while a sensitivity analysis was conducted based on the WLO Low scenario 2050 prices to assess the impact of different fuel price trajectories on the results.

WLO Scenarios

The WLO scenarios are two distinct storylines based on different climate commitment trajectories. The WLO High scenario assumes that a generally strong global commitment towards climate change, where all national 2020 climate pledges, committed at the UN climate negotiations are fulfilled. On the other hand, the WLO Low scenario assumes a low global commitment, where only unconditional 2020 pledges are fulfilled. The two distinct storylines lead to substantially different price trajectories and expected global temperature rise of 2.5-3°C and 3.5-4°C, respectively. The detailed scenario assumptions can be found in [15].

It is noted that the WLO High and Low scenarios utilised in the MAC curve analysis fall short of the 2°C commitment of the Paris Agreement, as well as the currently stipulated EU and Dutch climate commitments. However as noted in [15], projected fuel prices for a 2°C scenario are not readily available and the uncertainty associated with the projected CO_2 prices rises drastically. Hence, the WLO High scenario prices are used as reference prices instead.

Table 43: Projected prices in 2025, 2030 and 2050

Price Type	Unit	2025	2030	2050 (WLO Low)	2050 (WLO High)	References
Natural Gas Price	€$_{2018}$/GJ	7.27	7.9	11	5.5	[14–15]
Average Wholesale Electricity Price	€$_{2018}$/MWh	43	57	94.8	105.4	[14–15]
Biomass Price	€$_{2018}$/GJ	NA	5.9/6.3[46]	10.7	22.1	[15]
Carbon Price	€$_{2018}$/ton CO_2	NA	47	42.1	168.6	[14–15]
Wholesale Steam Price	€$_{2018}$/GJ	13 (4 – 20); assumed constant price				[74–96]
Oxygen *Considered profit for the AEL and PEM technologies*	€$_{2018}$/ton	26.50 (13-40); assumed constant price				[74]

COMBINED HEAT & POWER (CHP) EMISSION ATTRIBUTION METHOD

The steam and electricity emission factors ($EF_{CHP,heat}$ and $EF_{CHP,el}$, respectively) are determined based on attribution method suggested in [31], with the adapted formulas as follows:

$$EF_{CHP,heat} = Em_{CHP} * A_{CHP,heat}/Q_{net}$$

$$EF_{CHP,el} = Em_{CHP} * A_{CHP,el}/EL_{net}$$

$\mathrm{EF_{CHP,heat}}$ = Steam emission factor (kg/GJ)
$\mathrm{EF_{CHP,el}}$ = Electricity emission factor (kg/GJ)
$A_{CHP,heat}$ = Attribution factor for heat
$A_{CHP,el}$ = Attribution factor for electricity
Q_{net} = net steam output
EL_{net} = net electricity output

Where Em_{CHP}, $A_{CHP,heat}$ *and* $A_{CHP,el}$ are calculated as follows:

$$Em_{CHP} = EF_i * F_i$$

$$A_{CHP,heat} = \frac{\eta_{heat}/\eta_{ref,heat}}{\eta_{heat}/\eta_{ref,heat} + \eta_{el}/\eta_{ref,el}}$$

$$A_{CHP,heat} = \frac{\eta_{el}/\eta_{ref,el}}{\eta_{heat}/\eta_{ref,heat} + \eta_{el}/\eta_{ref,el}}$$

Em_{CHP} = Emissions from the CHP (kg)

[46] 5.9 and 6.3 are biomass price (€$_{2018}$) quoted from the WLO Low and WLO High Scenarios, respectively.

EF_i = Emission factor (kg/GJ) for the fuel type *i*

F_i = Fuel consumption (GJ)

η_{heat} = Thermal efficiency of the CHP

η_{el} = Electrical efficiency of the CHP

$\eta_{ref,heat}$ = Reference efficiency for steam production in a stand-alone boiler (85%) [129]

$\eta_{ref,heat}$ = Reference efficiency of electricity production without cogeneration (52.5%) [129]

A.5. RESULTS & DISCUSSION

MAIN RESULTS

Table 44: Marginal abatement costs for the decarbonisation options – Maasvlakte production site

Technology	Percentage of Abatement	Marginal Abatement Cost – Excluding Carbon Price (€$_{2018}$/ton of CO_2)	Marginal Abatement Cost – Including Carbon Price (€$_{2018}$/ton of CO_2)
Partial Post-Combustion CCS (Residual Fuel Streams only)	13%	-53.2	-105.4
Complete Post-Combustion CCS	79%	18.6	-33.6
Hydrogen Boiler + Off-site Blue H_2	84%	33.4	-18.8
Biomass Boiler	100%	37.9	-15.8
Hydrogen Boiler + Off-site Green H_2	100%	39.2	-13.1
Electrode Boiler	100%	105.8	52.1
Hydrogen Boiler + On-site AEL	100%	247.9	195.7
Hydrogen Boiler + On-site PEM	100%	296.3	244.0

Table 45: Marginal abatement costs for the decarbonisation options – Botlek production site

Technology	Percentage of Abatement	Marginal Abatement Cost – Excluding Carbon Price (€$_{2018}$/ton of CO_2)	Marginal Abatement Cost – Including Carbon Price (€$_{2018}$/ton of CO_2)
Complete Post-Combustion CCS	85%	68.6	16.4
Partial Post-Combustion CCS (Residual Fuel Streams only)	48%	70.5	18.2
Hydrogen Boiler + Offsite Green H_2	100%	83.9	31.6
Hydrogen Boiler + Offsite Blue H_2	89%	85.8	33.6
Biomass Boiler	100%	96.3	42.6
Hydrogen Boiler Retrofit + Offsite Green H_2	79%	116.1	63.5
Hydrogen Boiler Retrofit + Offsite Blue H_2	69%	118.5	65.9
Electrode Boiler	100%	142.8	89.0
Hydrogen Boiler + On-site AEL	100%	226.6	174.4
Hydrogen Boiler + On-site PEM	100%	259.7	207.4
Hydrogen Boiler Retrofit + On-site AEL	79%	344.0	291.4
Hydrogen Boiler Retrofit + On-site PEM	79%	396.7	344.2

SENSITIVITY ANALYSIS – PRICING TRAJECTORIES (WLO LOW SCENARIO)

Table 46: Marginal abatement costs for the decarbonisation options, with reference to WLO Low Scenario – Maasvlakte production site

Technology	Percentage of Abatement	Marginal Abatement Cost – Excluding Carbon Price ($€_{2018}$/ton of CO_2)	Marginal Abatement Cost – Including Carbon Price ($€_{2018}$/ton of CO_2)
Partial Post-Combustion CCS (Residual Fuel Streams only)	13%	-54.8	-77.3
Biomass Boiler	100%	-12.1	-41.6
Hydrogen Boiler + Offsite Green H2	100%	39.2	16.3
Hydrogen Boiler + Offsite Blue H2	84%	51.9	289.0
Complete Post-Combustion CCS	79%	56.2	33.6
Electrode Boiler	100%	95.2	65.69
Hydrogen Boiler + On-site AEL	100%	226.6	203.7
Hydrogen Boiler + On-site PEM	100%	274.3	251.4

Table 47: Marginal abatement costs for the decarbonisation options, with reference to WLO Low Scenario – Botlek production site

Technology	Percentage of Abatement	Marginal Abatement Cost – Excluding Carbon Price ($€_{2018}$/ton of CO_2)	Marginal Abatement Cost – Including Carbon Price ($€_{2018}$/ton of CO_2)
Biomass Boiler	100%	54.0	24.5
Hydrogen Boiler + Offsite Green H_2	100%	74.1	51.2
Complete Post-Combustion CCS	85%	76.2	53.5
Partial Post-Combustion CCS (Residual Fuel Streams only)	48%	78.1	55.4
Hydrogen Boiler + Offsite Blue H_2	89%	86.7	63.7
Hydrogen Boiler Retrofit + Offsite Green H_2	79%	108.1	74.3
Electrode Boiler	100%	127.4	97.9
Hydrogen Boiler Retrofit + Offsite Blue H_2	69%	128.7	94.8
Hydrogen Boiler + On-site AEL	100%	202.2	179.3
Hydrogen Boiler + On-site PEM	100%	234.8	211.9
Hydrogen Boiler Retrofit + On-site AEL	79%	312.8	278.9
Hydrogen Boiler Retrofit + On-site PEM	79%	364.8	330.9

PARTIAL CCS + OTHER TECHNOLOGY COMBINATIONS

Table 48: Marginal abatement costs for the different technological combinations – Maasvlakte site

Technology	Percentage of Abatement	Marginal Abatement Cost – Excluding Carbon Price ($€_{2018}$/ton of CO_2)	Marginal Abatement Cost – Including Carbon Price ($€_{2018}$/ton of CO_2)
Partial CCS + Hydrogen Boiler (Blue H_2)	81%	19.9	-32.3
Partial CCS + Hydrogen Boiler (Green H_2)	95%	26.8	-25.4
Partial CCS + Biomass Boiler	95%	32.3	-21.3
Partial CCS + Electrode Boiler	95%	85.7	32.1
Partial CCS + Hydrogen Boiler (On-site AEL)	95%	207.8	155.6
Partial CCS + Hydrogen Boiler (On-site PEM)	95%	249.7	197.5

Table 49: Marginal abatement costs for the different technological combinations – Botlek site

Technology	Percentage of Abatement	Marginal Abatement Cost – Excluding Carbon Price ($€_{2018}$/ton of CO_2)	Marginal Abatement Cost – Including Carbon Price ($€_{2018}$/ton of CO_2)
Partial CCS + Hydrogen Boiler (Green H_2)	92%	68.7	16.4
Partial CCS + Hydrogen Boiler (Blue H_2)	86%	68.7	16.4
Partial CCS + Biomass Boiler	92%	75.2	22.2
Partial CCS + Electrode Boiler	92%	96.7	43.8
Partial CCS + Hydrogen Boiler (On-site AEL)	92%	147.6	95.4
Partial CCS + Hydrogen Boiler (On-site PEM)	92%	165.9	113.6