PBL Netherlands Environmental
Assessment Agency

DECARBONISATION OPTIONS FOR THE DUTCH BOTTLE-GRADE PET INDUSTRY

A. Tran, K.J. West

07 May 2021

MIDDEN

Manufacturing Industry Decarbonisation Data Exchange Network

Decarbonisation options for the Dutch bottle-grade PET industry
© PBL Netherlands Environmental Assessment Agency; © TNO
The Hague, 2021
PBL publication number: 4617
TNO project no. 060.47868 / TNO 2021 P10748

Authors
A. Tran and K.J. West

Acknowledgements
We are grateful for feedback from Ashwin Briedjlal, Wout Fornara, John Sluijmers, and Paul Straatman (Indorama Ventures Europe B.V.).

MIDDEN project coordination and responsibility
The MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network) was initiated and is also coordinated and funded by PBL and TNO. The project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. Correspondence regarding the project may be addressed to:
Dick van Dam (PBL), dick.vandam@pbl.nl, or Silvana Gamboa Palacios (TNO), silvana.gamboapalacios@tno.nl.

This publication is a joint publication by PBL and TNO and can be downloaded from: www.pbl.nl/en. Parts of this publication may be reproduced, providing the source is stated, in the form: Tran, A., & West, K. J. (2021). Decarbonisation options for the Dutch bottle-grade PET industry. PBL Netherlands Environmental Assessment Agency & TNO, The Hague.

PBL Netherlands Environmental Assessment Agency is the national institute for strategic policy analysis in the fields of the environment, nature and spatial planning. We contribute to improving the quality of political and administrative decision-making by conducting outlook studies, analyses and evaluations in which an integrated approach is considered paramount. Policy relevance is the prime concern in all of our studies. We conduct solicited and unsolicited research that is both independent and scientifically sound.

TNO Energy Transition has a twofold mission: to accelerate the energy transition and to strengthen the competitive position of the Netherlands. TNO Energy Transition conducts independent and internationally leading research and we stand for an agenda-setting, initiating and supporting role for government, industry and NGOs.

This report was reviewed by Indorama Ventures Europe B.V.
PBL and TNO remain responsible for the content. The decarbonisation options and parameters are explicitly not verified by the companies.

Contents

List of abbreviations and acronyms

Abbreviation or acronym	Meaning
4-CBA	4-Carboxybenzaldehyde
A-PET	Amorphous polyethylene terephthalate
BHET	Bishydroxyethyl terephthalate
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CP	Continuous polymerization
CTA	Crude terephthalic acid
CSD	Carbonated soft drinks
FDCA	2,5-Furandicarboxylic acid
GHG	Greenhouse gas
HET	Hydroxyethyl terephthalate
Indorama Rotterdam	Indorama Ventures Europe B.V.
IV	Intrinsic viscosity
IVL	Indorama Ventures Public Company Limited
LHV	Lower heating value
MEG	Mono-ethylene glycol
MIDDEN	Manufacturing industry decarbonisation data exchange network
MX	Meta-xylene
PEF	Polyethylene 2,5-furandicarboxylate
PET	Polyethylene terephthalate
PIA	Purified isophthalic acid
PLA	Polylactic acid
PTA	Purified terephthalic acid
PX	Para-xylene
rPET	Recycled polyethylene terephthalate
t, kt, Mt	Tonne (10^3 kg), kilotonne (10^6 kg), megatonne (10^9 kg)
y	Year

FINDINGS

Summary

Indorama Rotterdam is a petrochemical company which specializes in the production of bottle-grade PET (polyethylene terephthalate) pellets and PTA (purified terephthalic acid) powder. Indorama, located in the Europoort section of the Port of Rotterdam, is the largest producer of bottle-grade PET and PTA in the Netherlands. In 2016, Indorama Rotterdam accounted for 125 $ktCO_2$-eq of greenhouse gas emissions. Bottle-grade PET is used in the manufacturing of packaging (mainly beverage bottles). PET is produced by esterifying and polymerizing PTA and MEG (mono-ethylene glycol). PTA is for a key material input to PET production and is produced by oxidizing PX (para-xylene). Indorama Rotterdam produces PTA for its on-site PET production, as well as PTA that is shipped to other facilities. Indorama Rotterdam has 426 kt of bottle-grade PET production capacity and 700 kt of PTA production capacity. The processes at Indorama Rotterdam require electricity, steam and heat which are provided by an on-site natural gas-fired CHP and natural gas boiler, complemented by grid electricity.

Table S1: Estimated energy consumption and emissions for PET and PTA production.

	2016 estimate
Greenhouse gas emissions [$ktCO_2$-eq]	125
Electricity consumption [TJ]	326
Steam consumption [TJ]	406
Direct heat consumption [TJ]	730

Source: Greenhouse gas emissions based on reported EU ETS emissions (NEa, n.d.). Energy consumption estimated based on author calculations for 350kt PTA and 400kt PET capacity with 80% utilization. See Chapter 2 for additional information.

Key decarbonisation options for bottle-grade PET production include:

- **Fuel substitution**: Emissions from natural gas combustion can be reduced via fuel substitution. Biogas, green gas, electricity, and hydrogen have all been considered. Green gas could be directly substituted using existing equipment, while biogas and hydrogen would require retrofits. Electrification of the utilities would require the replacement of existing equipment and supplemental grid electricity consumption.
- **Energy efficiency**: Process substitution could be used to increase the energy efficiencies of the technologies which produce bottle-grade PET and PTA. Residual heat, particularly from PTA production, can also be recovered and reused to decrease the overall energy demand. Mechanical vapour recompression could be used to increase the temperature of residual heat, potentially in combination with thermal storage.
- **Material efficiency, material substitution and circularity**: Increasing the recycled content of bottle-grade PET and using MEG and PX from biomass could help to reduce the emissions upstream and downstream in the value chain. Changing the product design and using alternative materials could also potentially yield additional emissions reductions, both directly in the process and in other parts of the supply chain.

This report describes the current status of the bottle-grade PET production by Indorama in the Netherlands, and discusses potential decarbonisation options. The estimates and descriptions in this report are based on publicly available literature and data, and have been reviewed by Indorama Rotterdam.

FULL RESULTS

Introduction

The Climate Agreement set out the ambitions to decrease the total CO_2 emissions in the Netherlands by at least 49% in 2030 compared to 1990 levels (Afspraken van het Klimaatakkoord, 2020). This is in line with the goals set by the Paris agreement: a maximum increase in average global temperature of 2°C, and preferably limiting global average temperature rise to 1.5°C. The MIDDEN project – the Manufacturing Industry Decarbonisation Data Exchange Network – aims to support industry, policy makers, analysts and the energy sector in their common efforts to achieve deep decarbonisation, by providing data and analysis on the industrial sector of the Netherlands. This report describes the current situation of the Dutch bottle-grade PET and PTA sector and the options and conditions for its decarbonisation.

Scope

Production locations
This report describes the current situation for the production activities of Indorama Ventures Europe B.V. in the Netherlands (henceforth "Indorama Rotterdam"), which is a subsidiary of Indorama Ventures Public Company Limited (henceforth "IVL"). IVL is active in 31 countries on five continents, and has a large number of subsidiaries. This report focuses only on Indorama Rotterdam, located in the Europoort area of the Port of Rotterdam.

Products
Indorama Rotterdam is the largest producer of PTA and bottle-grade PET in the Netherlands.

Processes
The key processes in PTA and bottle-grade PET production are oxidation, crystallization, separation, drying, solvent recovery, esterification, polymerization, cooling, and chipping. These are described in Section 2.

The main options for decarbonisation are:

- Fuel substitution (biogas, green gas, electricity, or hydrogen)
- Energy efficiency
- Material efficiency and substitution.

Reading guide

Section 1 introduces the Dutch bottle-grade PET and PTA industry. Section 2 describes the current situation for PTA and bottle-grade PET production processes in the Netherlands, and Section 3 describes the relevant products of these processes, while options for decarbonisation are systematically quantified and evaluated in Section 4. The feasibility and requirements of those decarbonisation options are discussed in Section 5.

1 Bottle-grade PET and PTA production in the Netherlands

1.1 Indorama Ventures Europe B.V.

IVL is a global company which produces a wide range of petrochemical products (Indorama Ventures, n.d.-f). The head office of IVL is in Bangkok, Thailand, and it operates sites in 31 countries on five continents (Indorama Ventures, n.d.-j). In 2019, IVL's revenue was USD 11.4 billion (Indorama Ventures, 2021). Indorama Rotterdam, the subsidiary of IVL located in the Netherlands, produces bottle-grade PET (polyethylene terephthalate) and PTA (purified terephthalic acid) at a 48.2 hectare site at the Europoort area of the Port of Rotterdam (Indorama Ventures, n.d.-c; Port of Rotterdam, 2016). PTA is used as a precursor for bottle-grade PET.

Figure 1. The location (bottom) and photo of (top) of Indorama Rotterdam.

Sources: Indorama Ventures (n.d.-b) and Port of Rotterdam (2016)

Indorama Rotterdam is the only producer of bottle-grade PET and PTA in the Netherlands (CPME, n.d.; PDC, 2012). In 2016, Indorama Rotterdam had 230 employees (Port of Rotterdam, 2016). Figure 1 gives the location and a photo of Indorama Rotterdam. Figure 2 shows bottle-grade PET and PTA at standard conditions.

Figure 2. Bottle-grade PET (left) and PTA (right) at standard conditions.

Sources: Indiamart (n.d.) and Indorama Ventures (n.d.-f)

1.2 History

The Indorama Rotterdam site was originally owned by Eastman Chemical, where production of bottle-grade PET and PTA began in 1998 (Sinclair, 1998; De Volkskrant, 1996). The decision to start these manufacturing activities at this location was based on the availability of a highly-skilled workforce, the suitability of raw materials from nearby oil refineries, and the accessibility of the site (De Volkskrant, 1995). Eastman Chemical changed the name of the site to Voridian Europoort B.V. (RVO, 2015; Taylor, 2001). In 1998, a utilities facility, called Europoort Utility Partners, was also built nearby to supply energy for the production activities, as a joint venture of Eneco (50%) and Air Products (50%) (Lukkes, n.d.; Port of Rotterdam, 2007).

In 2008, IVL acquired the PTA and PET production facility and continued operating under the name of Indorama Holdings Rotterdam B.V (Indorama Ventures, n.d.-b). In 2010, the utilities were acquired by IVL as well (Indorama Ventures, 2011). The name of the utilities facility then changed to Indorama Ventures Europe utility island (Port of Rotterdam, 2016). The entire site, including the utility island, is now called Indorama Ventures Europe B.V (Indorama Ventures, n.d.-b).

1.3 Local infrastructure

The port of Rotterdam has its own energy infrastructure, and Indorama Rotterdam is connected to this network (Figure 3) (Port of Rotterdam, 2019a). Indorama Rotterdam has its own utilities facility on site where steam is generated.

Though specific suppliers are unknown, there is capacity in Port of Rotterdam to produce necessary feedstocks and material inputs to bottle-grade PET production, such as para-xylene (PX) at the ExxonMobil Chemical Aromatics Plant, and mono-ethylene glycol (MEG) at Shell Nederland Chemie (Port of Rotterdam, 2016). IVL also owns Wellman Recycling Spijk, a PET recycling facility (Indorama Ventures, n.d.-g).

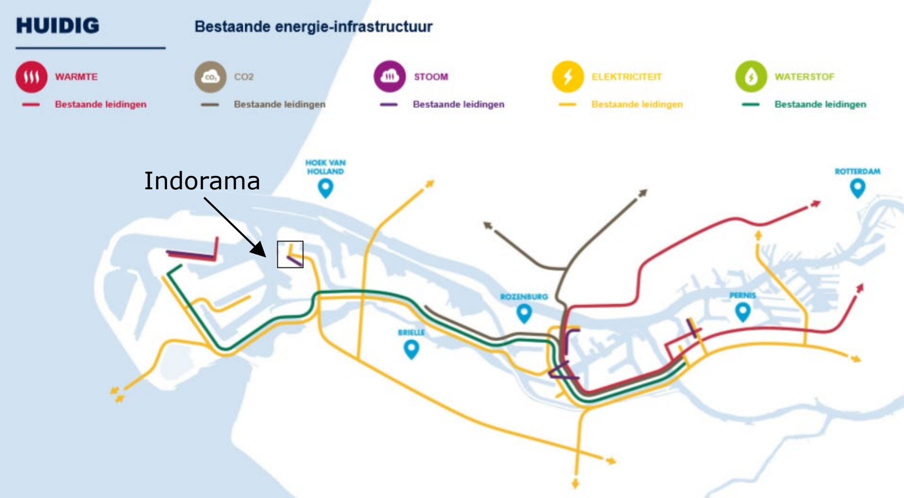

Figure 3. Existing energy infrastructure of Port of Rotterdam, in 2019.

Source: Port of Rotterdam (2019a)

Note: The captions translate to: Title: "CURRENT Existing energy infrastructure." In red: heat, in gray: CO_2, in purple: steam, in yellow: electricity, and in green: hydrogen. "Bestaande leidingen" = existing pipelines.

1.4 Production capacity

Since the start of operations at the site in 1998, its PET and PTA production capacities have increased several times (Table 1). In 2018, PTA capacity was doubled. PTA produced at the site is used for bottle-grade PET production in Rotterdam, but also shipped to other PET producing sites. This report focuses on 2016, as the most recent year when statistics were available for typical operations. During 2017, the PTA expansion was underway, and at the time of writing 2018 statistics were incomplete.

Table 1. Annual production capacity of Indorama Rotterdam of PET and PTA.

Year	PET capacity (kt/y)	PTA capacity (kt/y)	Source
1998	130	290	Sinclair (1998)
2010	200	350	Port of Rotterdam (2010)
2012	390	350	Murray (2010)
2016	400	350	Port of Rotterdam (2016)
2018	426	700	Indorama Ventures (n.d.-a, n.d.-b) Popovic (2017)

The utilities facility contains a natural gas CHP installation (GE LM2500 gas turbine) with electrical capacity of 23.7 MW_e, and an auxiliary natural gas boiler (EEA, 2019; General Electric, n.d.) with a capacity of 65 tonnes of 40 bar steam per hour. Other on-site utilities include cooling towers, a waste gas expander, two air compressors, and a water demineralizer.

1.5 Greenhouse gas emissions

Indorama Rotterdam is a large producer of PET and PTA, both fossil fuel-intensive processes that produce large amounts of CO_2 emissions. Figure 4 shows reported direct CO_2 emissions from the site, from 2005 to 2020, from the Dutch Emissions Authority database (NEa, n.d.). Though throughout this period the CO_2 emissions were reported under three institutional names (Europoort Utility Partners V.O.F., Indorama Holdings Rotterdam B.V., and Indorama Ventures Europe B.V.), the emissions were always reported with the same permit number. Because of changes in capacity and maintenance-related shutdowns, this report uses 2016 as a representative base year (Polyestertime, 2018; S&P Global, 2019).

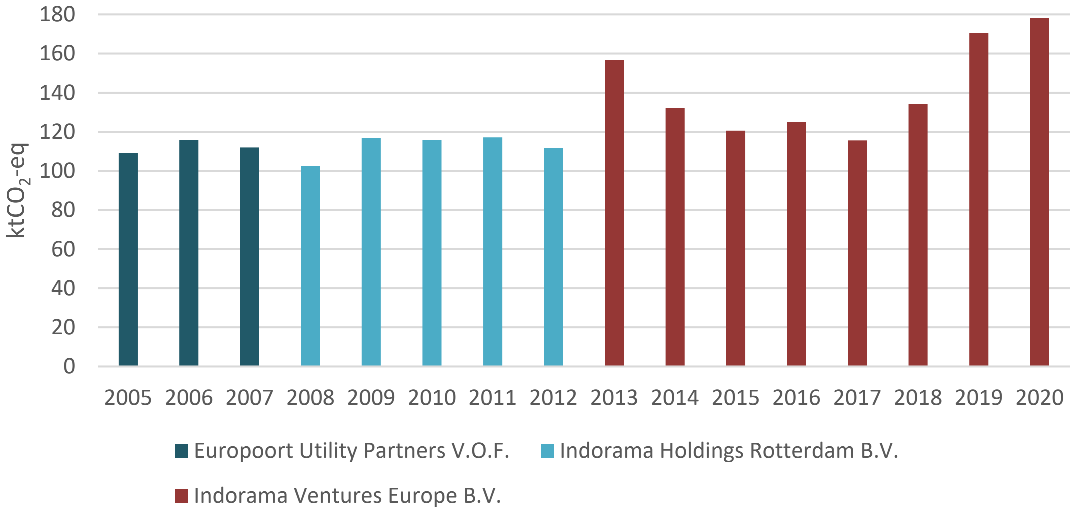

Figure 4. Greenhouse gas emissions from 2005 to 2020.

Source: NEa (n.d.)
Note: Permit number NL-200400249.

2 Bottle-grade PET and PTA processes

2.1 Bottle-grade PET value chain

The PET value chain starts with crude oil (Levi & Cullen, 2018). Ethylene, PX (para-xylene), and MX (meta-xylene) are produced via refining and steam cracking. These three commodities are processed into MEG (mono-ethylene glycol), PTA and PIA (purified isophthalic acid), respectively. These three precursors are then used in the production of bottle-grade PET. The upstream value chain for non-fiber PET (including bottle-grade PET) is shown in Figure 5, including the global annual production in 2013 of the relevant commodities in million tonnes per year (Mt/y). 33%[1] of the global PET production was non-fiber in 2013. The category of non-fiber PET is mostly made up of bottle-grade PET (around 77% in 2016) (Plastics Insight, n.d.-a). Bottle-grade PET is transported to packaging manufacturers for further processing. At the end of product lifetimes, PET is either recycled or discarded as waste (typically incinerated).

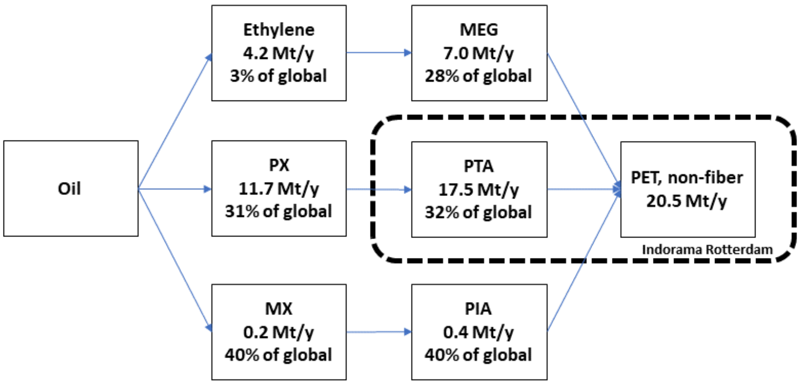

Figure 5. The non-fiber PET value chain.

Source: Levi & Cullen (2018)

2.2 Technical description of bottle-grade PET

PET, or polyethylene terephthalate, is a polymer made of chains of the monomer ethylene terephthalate (CPME, 2017). This monomer is produced by the bonding of two chemicals: PTA and MEG. A polymer is a large chain of a repeating chemical structure. Ethylene terephthalate is an ester, which means PET fits the scientific definition of a "polyester". However, the term polyester often colloquially refers to fiber-grade PET (commonly used in the textile industry). In this report, for clarity, we will refer to PET, bottle-grade PET, and fiber-grade PET, rather than polyester.

One of the most important characteristics of PET is its intrinsic viscosity (IV), which depends on the number of monomers that make up each polymer (Thiele, 2007). The IV of PET can be

---

[1] This only includes PET which is produced by the PTA route, which is used for about 98% of PET production.

estimated using the Billmeyer equation, based on the dilution into a solvent (Farah, Kunduru, Basu, & Domb, 2015), and is measured in units of deciliters per gram (dL/g). This is the inverse of polymer solution concentration. Intrinsic viscosity varies depending on the PET product; the manufacturer is able to control the IV by prolonging or shortening the polymerization process, to give the final product the desired properties. PET with high intrinsic viscosity has polymers with long chains of monomers, which makes the molecular weight of the polymer high, and increases the rigidity of the PET. PET with shorter chains of monomers has the opposite characteristics: lower molecular weight and more flexibility. Bottle-grade PET requires PET polymers with relatively long chains of monomers. The other two grades of PET, fiber- and film-grade PET, require smaller numbers of monomers. Table 2 shows the typical IV and product examples for each of these three grades.

Table 2. The typical intrinsic viscosities of the three main classifications of PET

PET classification	IV (dL/g)	Product examples
Fiber-grade	0.40 - 0.70	Textile
Film-grade	0.60 - 0.70	BoPET (biaxially oriented PET film) (for example, used for flexible food packaging, paper coating, insulation)
Bottle-grade	0.70 - 0.85	Water bottles (IV: 0.70 - 0.78) Carbonated soft drink bottles (IV: 0.78 - 0.85)

Source: Gupta, & Bashir (2002)

Indorama Rotterdam specializes in the production of bottle-grade PET, with the highest IV. For bottle-grade PET, 2% of the PET mass is made up of PIA, or isophthalic acid, which is an isomer[2] of PTA (European Commission, 2016a).

2.3 PTA production processes at Indorama Rotterdam

PTA, or purified terephthalic acid, is a precursor of bottle-grade PET. PTA is produced by oxidizing PX, or para-xylene (CPME, 2016). Several processes for PTA production exist; a diagram of the Eastman process is shown in Figure 6 (Zein et al., 2010). Crude terephthalic acid (CTA) is an intermediate product in the production of PTA. Oxidizing para-xylene (PX) into PTA has a conversion factor of 98.3%. Indorama Rotterdam requires PTA with a minimum purity of 99.9% (Indorama Ventures, 2017a), which they achieve through the post-oxidation sub-process, which removes impurities and continues the oxidation process.

Indorama Rotterdam uses equipment supplied by GPT to produce PTA (GPT, n.d.; Indorama Ventures, n.d.-b), based on the Eastman process. The process is described by the mass flow and energy flow diagrams below (Figures 6 and 7).

---

[2] An isomer is a molecule with an identical chemical formula but a different spatial arrangement of atoms.

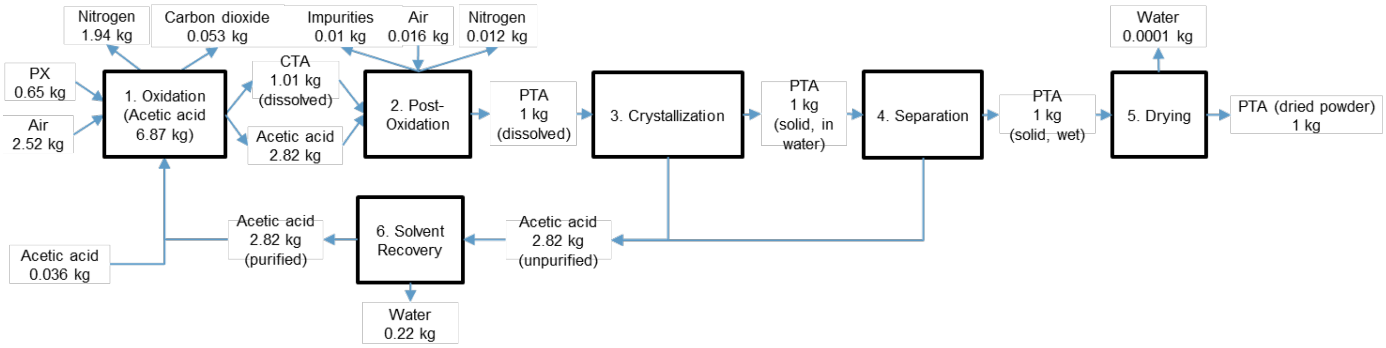

Figure 6. Mass flow diagram for 1 kg of PTA.

Source: Engineering ToolBox (2003a); Zein et al. (2010)

Note: The mass of air consists 23.14% of oxygen (Engineering ToolBox, 2003a).

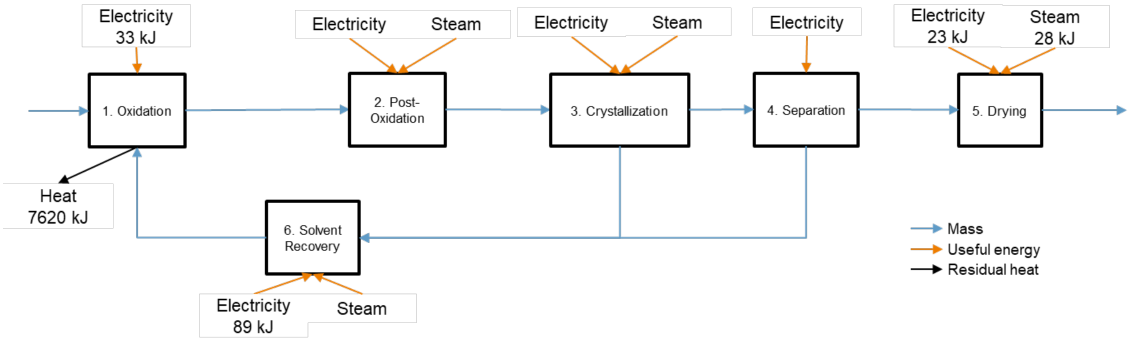

Figure 7. Energy flow diagram for 1 kg of PTA.

Sources: Cao, Chang, & Kaufman (2011); Neelis, Patel, Blok, Haije, & Bach (2007)

Note: The figure above shows author estimates based on publicly available literature. The value for residual heat is from Neelis et al. (2007) and the other values are from Cao et al. (2011). Reliable estimates were not available at this level of detail, but the full PTA production process requires 0.346 GJ electricity/t PTA and 0.981 GJ steam/t PTA (See Table 3).

1. **Oxidation**
   First, the PX (liquid) is oxidized into CTA (Cao et al., 2011; CPME, 2016). A mixture of PX, acetic acid (solvent), catalyst and compressed air is put into a bubble column reactor in liquid phase at a high temperature (175 - 225 °C) and pressure (15 - 30 bar). The high pressure is needed to keep PX in a liquid state. The conversion of PX into PTA has a yield of 98.3%, and the remaining 1.7% consists of unconverted PX and impurities (Zein et al., 2010). The oxidation reaction produces water (Figure 8). The partial burning of acetic acid causes acetic acid losses and CO_2 emissions. The oxygen needed for the reaction is supplied as compressed air. This process is exothermic so no additional heat is required, but some electricity is used for pumps and blowers.

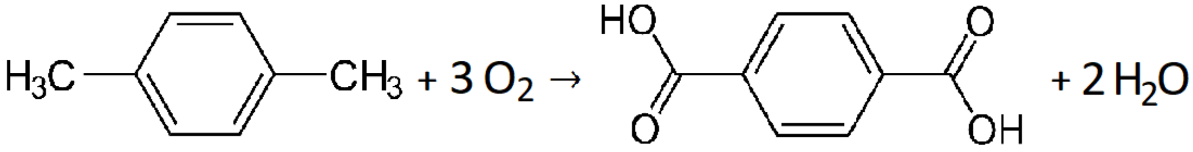

Figure 8. Chemical reaction: PX and oxygen react to form PTA and water.

Source: MCPI (2018)

2. **Post-Oxidation**
   To guarantee that the PTA has a high purity, the post-oxidation sub-process is used to remove impurities and to continue with the oxidation process. Post-oxidation increases the yield from 98.3% to 98.9% (Zein et al., 2010). The remaining PX is removed via digestion so that the PTA at least has a purity of 99.9%. Post-oxidation requires steam to reach the required temperature for oxidation and electricity for pumps and blowers.
3. **Crystallization**
   The resulting PTA is still dissolved in acetic acid and water. To produce solid PTA crystals, a crystallizer is used (Zein et al., 2010). The crystallizer separates water and acetic acid from the system, and at the same time forms solid PTA crystals (Skindzier, Kaplan, & Roberts, n.d.). The acetic acid and water continue to the solvent recovery sub-process. The crystallizer requires steam for heating and electricity for pumps and blowers.
4. **Separation**
   By using a vacuum flash drum and a rotary vacuum filter, most of the remaining acetic acid and water is separated and sent to the solvent recovery step (Zein et al., 2010). Separation equipment requires electricity.
5. **Drying**
   The solid PTA is completely dried into a powder. The dryer uses steam to heat air and electricity to circulate that air.
6. **Solvent Recovery**
   The acetic acid is recovered by distilling it out of a solution (Cao et al., 2011). Solvent recovery is crucial for decreasing the costs of producing PTA, as recovered acetic acid can be reused. Solvent recovery is relatively energy-intensive, requiring steam for distillation and electricity for pumps and blowers.

2.4 PET production processes at Indorama Rotterdam

The production of bottle-grade PET happens in two distinct stages. The first stage is melt polymerization, in a liquid state (Ma, 2005). Indorama Rotterdam uses technology from GPT and INVISTA for the melt polymerization stage (Indorama Ventures, n.d.-a; INVISTA, n.d.). Melt polymerization produces amorphous polyethylene terephthalate (A-PET), with IVs of 0.6 dL/g or lower (Ma, 2005). The second stage is solid state polymerization, which increases the IV of the PET product to around 0.8 dL/g in a solid state (Papaspyrides, & Vouyiouka, 2009). In addition to electricity and steam, heat transfer oil is also heated with two natural gas thermal oil heaters to provide heat for the process. Each thermal oil heater has an output of 14 MW$_{th}$, but they have different efficiencies: 92% and 107% (LHV basis). The PET production process is described by the mass flow and energy flow diagrams below (Figures 9 and 10).

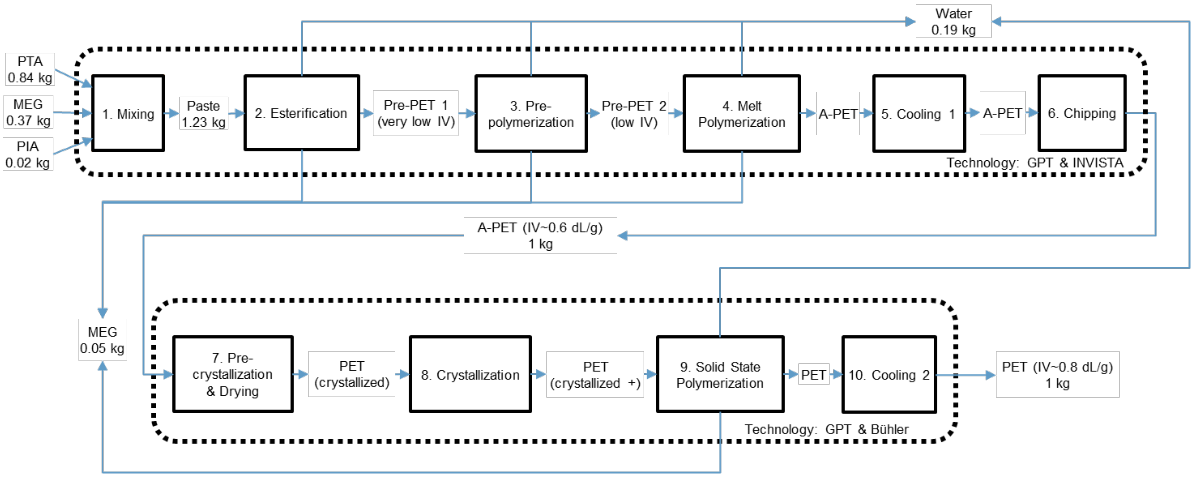

Figure 9. Mass flow diagram for 1 kg of bottle-grade PET.

Sources: European Commission (2016a) and Santhana Gopala Krishnan, & Kulkarni (2008)
Note: The figure above shows author estimates based on publicly available literature.

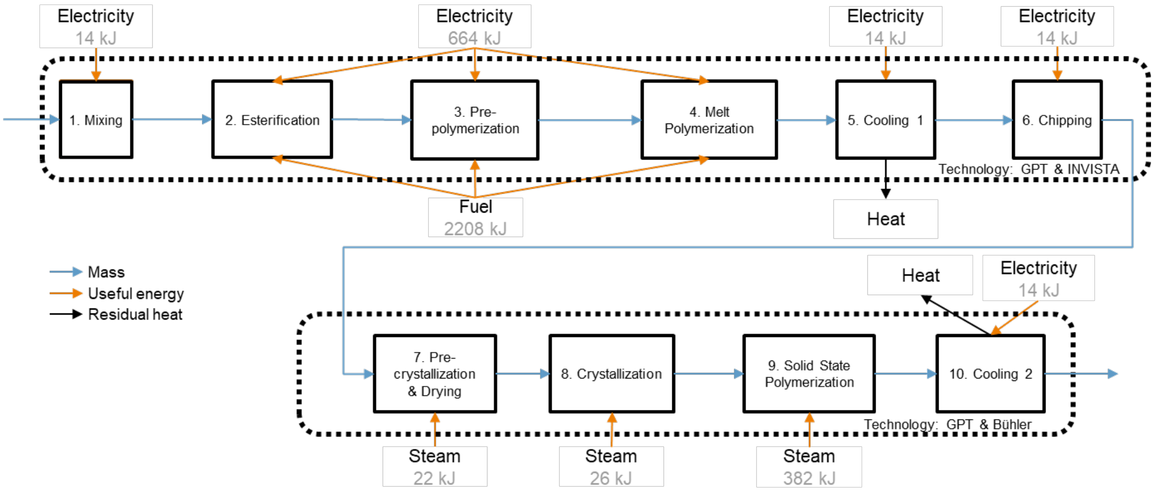

Figure 10. Energy flow diagram for 1 kg of bottle-grade PET.

Sources: CPME (2017), Papaspyrides, & Vouyiouka (2009) and Port of Rotterdam (2016)

Note: The figure above shows author estimates based on publicly available literature. The grey values are approximations, which were calculated by dividing the total energy [0.72 GJ electricity/t PET and 0.43 GJ steam/t PET] over the sub-processes proportionally to the residence time and temperature differential.

The overall chemical equation of PET production is shown by Figure 11. For bottle-grade PET, the number of monomers per chain (*n*) in this equation is typically between 100 and 200 (CPME, 2017). The chemical process of the bonding of PTA and MEG into PET is called a polycondensation reaction, because of the condensation of water that occurs.

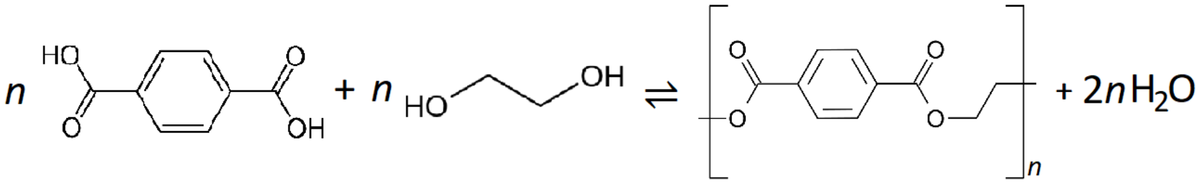

Figure 11. Chemical equation: *n* units of PTA reacts with *n* units of MEG to produce PET with *n* ethylene terephthalate monomers and water.

1. **Mixing**
   First, PTA, MEG and PIA are mixed together into a paste (slurry mixture). The molar ratio of PTA+PIA to MEG is 1:1.15 (Santhana Gopala Krishnan, & Kulkarni, 2008). An excess of MEG is needed to optimize the reaction rate. Electricity is required for mixing.
2. **Esterification**
   The next step is the production of pre-PET 1 (with very low IV) through the bonding of PTA, MEG and PIA into esters (ChemistryScore, n.d.). This process produces water and MEG as a by-product, and the resulting MEG is reused in the mixing sub-process. The chemical process to produce pre-PET 1 is done at standard pressure and at a high temperature (about 280 °C), in the presence of an antimony catalyst (CPME, 2017; INVISTA, n.d.; Köpnick, Schmidt, Brügging, Rüter, & Kaminsky, 2000). Water and MEG are removed throughout the whole PET production process to optimize the reaction rate. The residence time for esterification is about five hours and requires heat (provided via natural gas burners).
3. **Pre-polymerization** + 4. **Melt Polymerization**
   The pre-PET 1 is pre-polymerized in a vacuum, increasing its IV to produce pre-PET 2. As the IV of the PET product increases, pre-PET 2 is fed into a disk-shaped reactor (still in a vacuum), which optimizes the removal of water and MEG because of the increased surface area (Ma, 2005). Melt polymerization produces A-PET with an IV of about 0.6 dL/g. The third and fourth sub-processes are assumed to be operating at

about 300 °C (INVISTA, n.d.), with a combined residence time of about five hours. Heat (from natural gas burners) and electricity are required to create vacuum conditions.

5. **Cooling**
   The A-PET is then brought into contact with cooling water, solidifying it into long strands of about 2.5 mm thickness (Indorama Ventures, 2017b; UL Prospector, n.d.-a). Cooling requires electricity.
6. **Chipping**
   The strands of A-PET are chipped into solid and cubical PET pellets (Indorama Ventures, 2017b; UL Prospector, n.d.-a). These pellets have reached fiber-grade PET quality. Chipping requires electricity.
7. **Pre-crystallization and drying**
   The solid A-PET pellets are exposed to a hot nitrogen stream (185 °C, heated with steam) (Indorama Ventures, 2017b; Papaspyrides, & Vouyiouka, 2009). The PET crystallizes, into opaque white pellets, in about one hour. In this sub-process, as well as the crystallization and polymerization sub-processes, nitrogen is used instead of air to prevent oxidation by atmospheric oxygen (Köpnick et al., 2000).
8. **Crystallization**
   This sub-process is also done with exposure to a hot nitrogen stream (210 - 220 °C, heated with steam) (Papaspyrides, & Vouyiouka, 2009), with about one hour residence time.
9. **Solid-state polymerization**
   Solid state polymerization (SSP) increases the IV to the desired level for the final product, again by applying a hot nitrogen stream (205 - 215 °C, heated with steam) (Papaspyrides, & Vouyiouka, 2009). Solid state polymerization takes a relatively long time, about 15 hours. At the end of this sub-process, the pellets have the properties of bottle-grade PET, which has an IV of about 0.8 dL/g.
10. **Cooling**
    The bottle-grade PET pellets are cooled by blowing (non-heated) nitrogen over them (Indorama Ventures, 2017b). The final product at Indorama Rotterdam is an opaque, white, cylindrical 2.5mm pellet.

2.5 Utilities at Indorama Rotterdam

Most of Indorama's energy requirements for the production of PTA and bottle-grade PET comes from on-site utilities (Kreijkes, 2017; Port of Rotterdam, 2016). Indorama Rotterdam has a natural gas CHP installation (GE LM2500 gas turbine) with 23.7 MW_e capacity, and an auxiliary natural gas boiler with a capacity of 65 tonnes per hour of 40 bar steam (EEA, 2019; General Electric, n.d.). The CHP unit has a total efficiency of 81% and an electrical efficiency of 33%. Indorama Rotterdam uses the auxiliary boiler if additional steam is needed beyond the CHP unit output. The process steam demand can also be fully met by the auxiliary boiler, which has a capacity of 49.9 MW_{th} and an efficiency of about 92%. Depending on gas and electricity prices, Indorama Rotterdam can choose to operate the CHP unit, the auxiliary boiler or both (in combination with grid electricity).

2.6 Energy consumption and emissions

The consumption of useful energy for the production of 1 kg PTA and 1 kg bottle-grade PET is shown in Table 3.

Table 3. Useful energy for the production of 1 kg PTA and 1 kg bottle-grade PET.

Product	Electricity (MJ)	Steam (MJ)	Fuel (MJ)	Total (MJ)
PTA	0.346	0.981	0.000	1.327
PET	0.720	0.430	2.208	3.358

Sources: CPME (2017), Port of Rotterdam (2016) and Zein et al. (2010)

There are four main sources of CO_2 emissions in this process. Table 4 shows estimated direct CO_2 emissions for 2016. The relative shares of each source vary from year to year, depending on production levels and operation of utilities.

Table 4. Sources of CO_2 emissions in 2016.

Emissions source	Emissions ($ktCO_2$-eq)	Fraction (%)
Natural gas CHP	26.4	21
Natural gas boiler	35.2	28
Natural gas thermal oil heater	40.3	32
Acetic acid burning	23.1	19
2016 Total	125.0	100

Sources: CBS (2020), CPME (2016), EEA (2019), NEa (n.d.) and RVO (2019)

The water input for the production of 1 kg PTA and 1 kg bottle-grade PET is shown in Table 5. Because PTA production is exothermic, a large supply of cooling water is needed. This water is drawn from the canals around Indorama Rotterdam, and cooling towers are used to circulate the water.

Table 5. Water input for the production of 1 kg PTA and 1 kg bottle-grade PET (includes on-site utilities).

Product	Process water (kg)	Cooling water (kg)	Total (kg)
PTA	-	251.0	251.0
PET	0.5	9.6	10.1

Sources: CPME (2017) and Zein et al. (2010)

3 Bottle-grade PET and PTA products and applications

3.1 IVL products in the Netherlands

IVL groups its products in six product families: feedstock, PET, packaging, fibers, recycling, and wool (Indorama Ventures, n.d.-g). IVL has two subsidiaries in Netherlands: Indorama Ventures Europe B.V. (Indorama Rotterdam) (Indorama Ventures, n.d.-a) and Wellman Recycling Spijk (Indorama Ventures, n.d.-g). Indorama Rotterdam produces more PTA than is required for its production of PET, and the surplus is used to supply its other subsidiaries within Europe, such as IVL's facilities in Germany and Lithuania (Indorama Ventures, n.d.-b, n.d.-d, n.d.-e).

Wellman Recycling Spijk, IVL's other subsidiary in the Netherlands, produces recycled PET (rPET) flakes. This product is made by washing and chipping post-consumer PET into small flakes (Wellman International, n.d.). These rPET flakes are shipped to Wellman International Ireland to be processed into fiber-grade PET. This production process is not the focus of this report and thus will not be discussed in more detail.

Table 6. Products of IVL in the Netherlands.

Product family	Product Group	Products	Specification	Application	Location
Feedstock	PTA	PTA	-	PET	Rotterdam
PET	Bottle/Sheet	RAMAPET N180	IV = 0.80	General, non-reheat	Rotterdam
PET	Bottle/Sheet	RAMAPET R180	IV = 0.80	General, reheat	Rotterdam
PET	Bottle/Sheet	RAMAPET R182 (C)	IV = 0.82	Carbonated soft drinks, high-reheat	Rotterdam
PET	Bottle/Sheet	RAMAPET P184	IV = 0.84	Thick-walled products	Rotterdam
PET	Other/Specialties	RAMAPET R182 (C)	IV = 0.82	Carbonated soft drinks, fast-reheat	Rotterdam
Recycling	Flake	RM 7007FS rPET	1250 ppm colored flakes	Fiber, food-contact	Spijk
Recycling	Flake	RM 7004 rPET	2000 ppm colored flakes	Fiber, food-contact	Spijk

Source: Indorama Ventures (n.d.-c)

All the PET produced by Indorama Rotterdam is bottle-grade, but within this grade Indorama Rotterdam produces five types of bottle-grade PET, differentiated by application and IV. IVL calls its PET products RAMAPET, which is a brand name. The "R" in some product names stands for the presence of a reheat additive, which is used for increasing its heat absorption (PolyOne, n.d.). The "N" in product means the opposite: it does not contain reheat additive. "P" is used for a special type of RAMAPET used for thick-walled products. If a product name contains a "(C)" at the end, then it has properties which are especially suitable for carbonated soft drinks (CSD). The two types of RAMAPET R182 (C) have different applications: one is used for bottles or sheets and can be heated to a high temperature, while the other is used for specialties and can be quickly heated. The two types of rPET flakes which are made at Wellman Recycling Spijk are differentiated by the concentration of colored flakes. This differentiation is important for the quality of the products which are made from these flakes.

IVL describes RAMAPET **N180** as a general purpose, non-reheat PET resin for bottles, with an IV between 0.78 and 0.82 dL/g (Indorama Ventures, n.d.-h; UL Prospector, n.d.-a). RAMAPET N180 consists of cubical pellets with 2.5mm sides, and has the following applications for carbonated soft drinks, other beverage bottles, household products, food packaging, thermoformed containers, and pharmaceutical and medical applications.

RAMAPET **R180** is very similar to RAMAPET N180, but it is typically used for thermoformed containers. It contains a moderate level of reheat additive, allowing the molding of more complicated shapes and an efficient molding of light-weighted designs (Omnexus, n.d.-a; UL Prospector, n.d.-b). Reheat additive makes the product more able to absorb heat, which makes the energy consumption for PET pellet processing up to 30% lower compared to non-reheat PET (PolyOne, n.d.), without changing its appearance. RAMAPET R180 can also be used for film.

RAMAPET **R182 (C)** can be used for the same applications as above, except pharmaceutical and medical applications (Omnexus, n.d.-b). It contains a high level of reheat additive. Its IV is between 0.80 and 0.84 dL/g, which makes these bottle-grade PET pellets more rigid than RAMAPET N180 and RAMAPET R180.

RAMAPET **P184** is a slowly crystallizing, non-reheat PET resin for thick-walled applications that require optimal transparency, with an IV between 0.82 and 0.86 dL/g (Indorama Ventures, n.d.-i; UL Prospector, n.d.-c). RAMAPET P184 is the least flexible bottle-grade PET produced by Indorama Rotterdam. It has applications for refillable bottles, large (10 to 20 liter) containers, thick-walled jars, and thermoformed containers.

3.2 Bottle-grade PET and PTA market

About 99% of global PTA production is used for the production of PET (Levi, & Cullen, 2018), but there are other products which can be made from PTA, such as polybutylene terephthalate (PBT) (Plastics Insight, n.d.-a). According to HDIN Research, IVL was in 2018 the world's fifth largest PTA producer, with roughly 5% of global production capacity.[3] Chinese companies have been rapidly building PTA capacity in recent years, with some analysts forecasting a global overcapacity as these Chinese plants capacities outpace global demand for PTA and PET production capacities. Plant size has increased in recent years as well, with Zhongtai Petrochemical building a 1.2 Mt/year plant, and Hengli Petrochemical building a 2.5 Mt/year plant. China's total PTA capacity was expected to reach nearly 70 Mt per year by the end of 2020 (Bork 2020).

---

[3] The top six producers are YiSheng, Hengli Petrochemical, Xianglu Petrochemical, Reliance Industries, Indorama, and BP (HDIN Research 2019).

IVL has the world's largest production capacity of bottle-grade PET (Indorama, n.d.-f). Its capacity reached 4200 kt capacity globally in 2017 (Figure 13) (Plastics Insight, n.d.-b). Indorama Rotterdam accounted for around 10% of IVL's worldwide bottle-grade PET production. According to Indorama, 1 in 5 PET bottles in produced globally is made from Indorama's resins (Indorama, n.d.-f). The markets for both PET and PTA change rapidly, and up-to-date publicly available information on capacities and production levels are limited.

PTA prices are heavily dependent on the price of feedstocks, including PX and MEG, which are both produced from oil (top graph in Figure 14) (ICIS, 2018). The bottle-grade PET price is volatile and also follows the prices of its precursors, MEG and PX (bottom graph in Figure 14) (Murray, 2018). Bottle-grade PET prices in Europe fell from almost 1,400 EUR/tonne in early 2012 to a low of about 850 EUR/tonne in 2016, as paraxylene and MEG prices also dropped considerably. From 2016 to 2018, bottle-grade PET prices in Europe recovered to almost their 2012 levels, following the general trend of crude oil prices during that period. PTA prices, similarly, increased through 2018, reaching a maximum of nearly 70 USD/tonne (over 80 EUR/tonne).

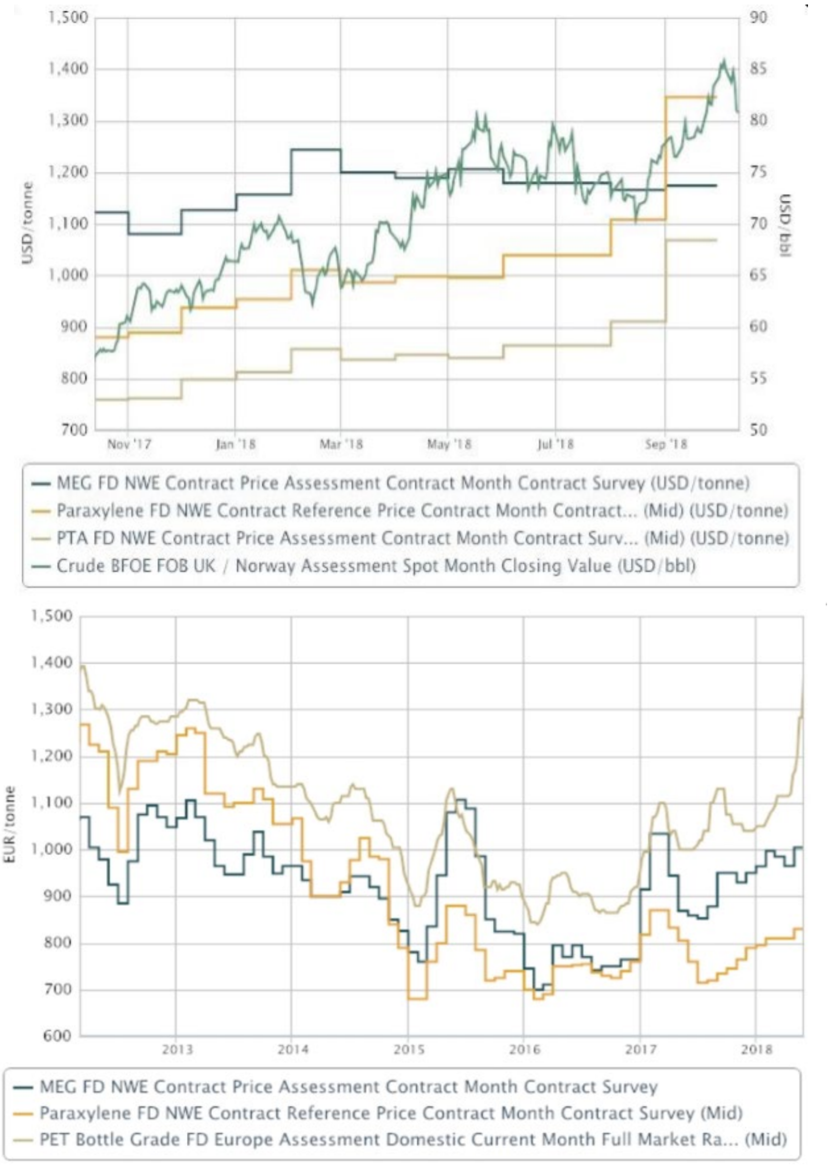

Figure 12. Top: The price curves of MEG, PX, PTA and crude oil, November 2017 to September 2018. Bottom: The price curves of MEG, PX and bottle-grade PET, 2012 to 2018.

Sources: ICIS (2018) and Murray (2018)

3.3 Applications of PTA

PTA has three main applications (Figure 15) (PlasticsInsight, n.d.-a). About 65% of the PTA was used for "Polyester Fiber" (made from fiber-grade PET), which is by far the largest of the three. "PET bottle resins" (made from bottle-grade PET) had a market share of 27%. The remaining 8% was filled by "Film" (made from film-grade PET). Fiber-grade PET is colloquially often called polyester[4], and is mainly used for textile production. Film-grade PET is used for the manufacturing of packaging films.

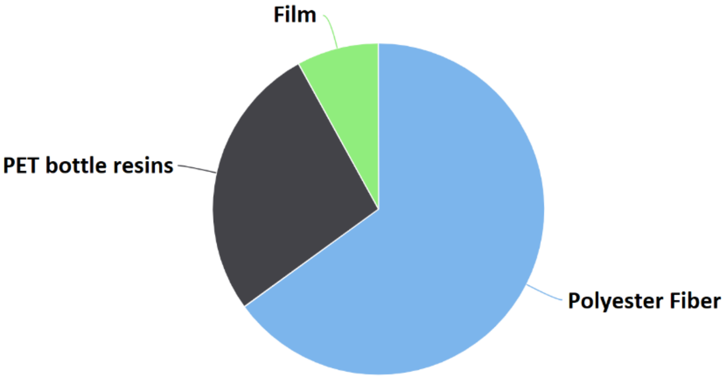

Figure 13. Applications of PTA in 2016.

Source: Plastics Insight (n.d.-a)

3.4 Applications of bottle-grade PET

Bottle-grade PET is used for many types of containers, mostly for the bottling of beverages (Figure 16) (Plastics Insight, n.d.-b). The figure depicts that in 2016 the markets for bottled water, carbonated soft drinks (CSD) and other drinks were responsible for 71% of the global bottle-grade PET consumption. The 14% used for sheet & film can be attributed to the application of bottle-grade PET in the thermoforming industry (Helmke, 2014), which presses PET sheets into the desired shape by using hot molds. Some packaging film types require the properties of bottle-grade PET.

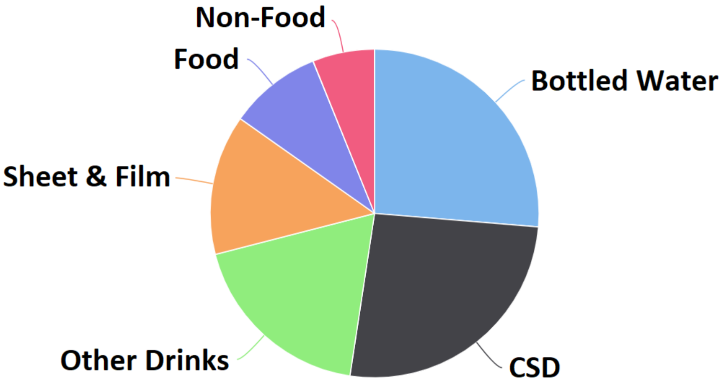

Figure 14. Applications of bottle-grade PET in 2016.

Source: Plastics Insight (n.d.-b)

Note: CSD = carbonated soft drinks

---

[4] Polyester as a chemical term can refer to many products, so this is called fiber-grade PET in this report.

After manufacturing, bottle-grade PET pellets are processed further by being melted and shaped into packaging products. During transport, the pellets absorb moisture from the environment (Indorama Ventures, n.d.-h). As moisture has a negative effect on the IV of PET during its melt processing, the PET pellets have to be dried again before they can be processed into containers. Manufacturing of PET bottles happens in two steps. First, the PET pellets are melted into pre-forms, which look like test tubes. The second step is called stretch blowing, in which the cylindrical preforms are re-heated and air is blown into them to create the desired shapes.

PET plastic has become one of the most widely used packaging materials due to several key advantages (Coca-Cola Nederland, 2017; ING, 2019): PET plastic is lightweight, flexible, and inexpensive to produce. This makes it convenient for transport, versatile, durable, and cost-efficient. However, PET plastics also has significant environmental impacts related to end-of-lifetime disposal of products made from PET. Low degradability means it can remain in the environment for thousands of years, if not recycled or incinerated, and can end up in the oceans where it is harmful to marine life. Recycling PET plastic can reduce the associated natural resource consumption and greenhouse gas emissions, but the share of PET that is not recycled remains high, and degradation of quality in the recycling process is a challenge. While public awareness of the environmental problems of plastic pollution has increasingly led to negative public opinion with respect to single-use plastic products, they remain ubiquitous.

At the end of product lifetimes, PET plastic is often not differentiated from the other plastic types. The European demand distribution of the different plastic types in 2017 is shown in Figure 17. In practice, different plastic types are often mixed in the same waste streams, which is problematic for recycling because of the cost and difficulty of separation. In the Netherlands and nine other European countries, landfilling of recyclable waste is restricted, which has led to a relatively high overall plastic packaging recycling rate, close to 50% in the Netherlands in 2016 (including PET and other plastic packaging), compared to an EU average of about 41%. The recycling rate in the Netherlands for post-consumer plastic packaging waste was lower, about 37%. (PlasticsEurope, 2018).

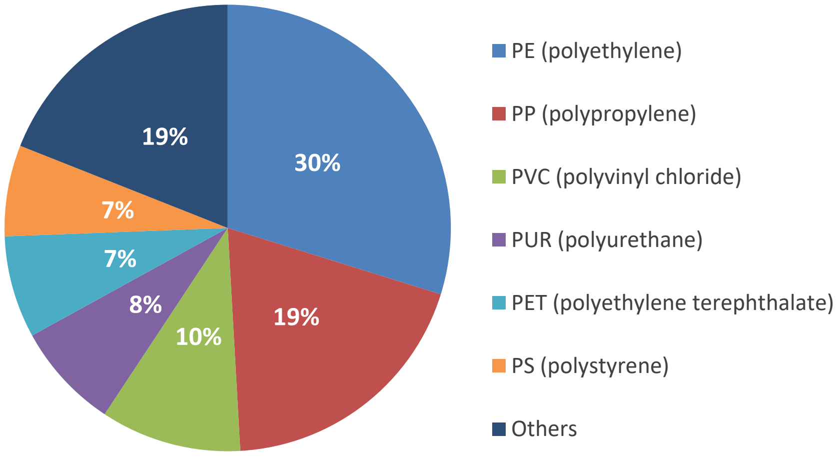

Figure 15. European plastic demand distribution in 2017.

Source: PlasticsEurope (2018)

4 Options for decarbonisation

4.1 Fuel substitution

Within the site boundaries, Indorama uses natural gas and grid electricity for the production of bottle-grade PET and PTA. Natural gas use is the main source of Indorama Rotterdam's direct emissions from fuel combustion. In 2016, 81% of their CO_2 emissions were from natural gas combustion (Table 4). Reducing natural gas use by switching fuels could therefore potentially provide large emissions savings. There are multiple options for decarbonisation via fuel substitution.

This section focuses on Scope 1 emissions, also called direct emissions, which are emitted on site. Scope 1 emissions include both fuel combustion emissions and process emissions from chemical reactions. Other sections include decarbonisation options which address Scope 2 emissions (emissions from purchased heat and electricity) and Scope 3 emissions (emissions from upstream and downstream processes related to the energy and material inputs of the process, including all other indirect emissions). Scope 3 emissions in particular are difficult to quantify without a full Life Cycle Assessment (LCA), but can be an important part of the impact of a product and its value chain. For plastics, for example, end-of-life combustion of products, which falls into Scope 3, is important.

4.1.1 Biogas

Biogas, produced via anaerobic digestion of biodegradable materials, can be used to replace natural gas. This is commonly produced from municipal solid waste, municipal waste water, crop residues, and animal manure. The net calorific value of biogas, about 23 MJ/Nm^3, depending on the source (SGC, 2012), is lower than that of natural gas (31.65 MJ/Nm^3) (RVO, 2019), which means that the biogas input rate needs to be about 38% higher to keep the same capacity. The most abundant components of biogas are methane (40-75 vol%) and carbon dioxide (15-60 vol%) (Bharathiraja et al., 2018). The composition of biogas is highly variable depending on the feedstock material and process. Hydrogen sulfide (H_2S) and moisture must be removed from the biogas, because they can corrode equipment (Van Dorp, 2013). The purification process requires additional equipment.

Retrofits to combustion equipment would also be necessary; existing burners would need to be replaced with biogas burners (Alm, Falk, Nightingale, & Zehr, 2011). To keep the same capacities, these burners have higher input rates than the original natural gas input rates. Tables 7, 8 and 9 give the economic data of replacing natural gas with biogas. Under EU ETS, biogas, and other biogenic energy carriers, are assumed to be net carbon neutral over their lifetimes. Although biogas technology is mature, the availability of low-cost biogas is a limiting factor to the implementation of this option. IEA's cost curve for global biogas supply in 2018 estimated that about 25 EJ (600 Mtoe) of biogas could be sustainably produced, with costs ranging from just above 2 EUR/GJ to about 26 EUR/GJ. The estimated potential would grow by 50% by 2050, with an average cost below 12 EUR/GJ[5] (IEA, 2020). Costs are highly dependent on technology choice, type of biomass, and availability of the biomass resources.

---

[5] Costs have been converted from USD to EUR2017 on the basis of a 2017 average exchange rate of 1.1297.

Today, about 14 PJ of biogas are produced in Netherlands, mainly via anaerobic digestion of agricultural waste and manure, with smaller shares from landfill gas recovery and sewage sludge (Scarlat et al., 2018). European biogas production costs are around 17 EUR/GJ, on average (IEA, 2020). This domestic production is insufficient for all potential applications of biogas, and future growth in supply and demand is uncertain. Competitiveness of biogas for this purpose will depend on future prices of different possible fuels and demand for biogas in other parts of the economy.

Table 7. Biogas purification plant, economic data[6].

Characteristics	Value	Source
Fuel	Electricity	Bailon Allegue, & Hinge (2014); Kvist (2011)
Avoided CO_2	Not applicable: decarbonisation occurs in combustion in the thermal oil heaters and boiler	
Capacity	200 – 2,000 m^3/hour (purified biogas from raw biogas)	Bailon Allegue, & Hinge (2014); Kvist (2011)
Efficiency	100%	
Lifetime	15 years	Bailon Allegue, & Hinge (2014); Kvist (2011)
CAPEX	134 – 595 EUR_{2017}/(m^3/hour)	Bailon Allegue, & Hinge (2014); Kvist (2011)
Fixed OPEX	3 – 30 EUR_{2017}/(m^3/hour)/year	Assumed 2-5% of CAPEX
TRL	9	
Market entry	Present	

Table 8. Retrofitting a biogas burner to the boiler, economic data.

Characteristics	Value	Source
Base year	2016	
Fuel	Purified biogas	
Avoided CO_2	35.2 kt (28% of 2016 level)	See Table 4
Capacity	300 – 1,200 kWth (burner output)	Heattec (n.d.)
Efficiency	80 – 85%	Alm et al. (2011)
Lifetime	25 years	
CAPEX	13 – 55 EUR_{2017}/kWth (biogas burner, steam output)	Alm et al. (2011); Heattec (n.d.); Van Berkel, & Hernandez (2018)
Fixed OPEX	0.3 – 2.7 EUR_{2017}/kWth/year (biogas burner, steam output)	Assumed 2-5% of CAPEX
TRL	9	
Market entry	Present	

---

[6] All cost data in this chapter is expressed in EUR_{2017}.

Table 9. Retrofitting a biogas burner to the two thermal oil heaters, economic data.

Characteristics	Value	Source
Base year	2016	
Fuel	Purified biogas	
Avoided CO_2	40.3 kt (32% of 2016 level)	See Table 4
Capacity	300 – 1,200 kWth (burner output)	Heattec (n.d.)
Efficiency	87 – 91%	Pirobloc (n.d.-a)
Lifetime	25 years	
CAPEX	12 – 50 EUR_{2017}/kWth (biogas burner, heat output)	Heattec (n.d.); Pirobloc (n.d.-a); Van Berkel, & Hernandez (2018)
Fixed OPEX	0.2 – 2.5 EUR_{2017}/kWth/year (biogas burner, heat output)	Assumed 2-5% of CAPEX
TRL	9	
Market entry	Present	

4.1.2 Green gas

Biogas can be upgraded to green gas, also called biomethane, by removing the CO_2, hydrogen sulfide (H_2S) and moisture (Van Dorp, 2013). Green gas, or biomethane, has similar properties and composition to natural gas, and thus could be used to replace natural gas directly, without retrofits to the CHP, boiler and thermal oil heater. Natural gas which has 100% CO_2 compensation is also called green gas (Essent, n.d.), but this section refers to upgraded biogas.

The upgrading process requires new equipment to remove CO_2. There are different technologies for the upgrading plant: water scrubbing, amine scrubbing, pressure swing adsorption, membrane separation and organic physical scrubbing (Danish Energy Agency, 2017). The different technologies have similar investment costs (SGC, 2013). However, the most commonly applied technology is water scrubbing. After upgrading to green gas, the gas has nearly the same net calorific value as natural gas. Further upgrading and purification could be used to reach H-gas quality (high calorific gas); alternatively, burner operation parameters could be adjusted to allow combustion of L-gas (low calorific gas) quality upgraded biogas. There may be an impact on efficiency of existing equipment. The existing utilities of Indorama Rotterdam, such as the CHP and the auxiliary boiler, could be operated with green gas.

Green gas could potentially also be transported to the site with the existing natural gas infrastructure; this would not be possible with biogas because it has different properties. Currently, the availability of green gas in the Netherlands is low, and it is not available for Indorama Rotterdam to purchase it via the existing gas pipelines (HIER, 2017).

Table 10 considers biogas purchase and an on-site upgrading plant. Although green gas technology is mature, the availability of biomass or biogas could be a constraint in the future.

Table 10. Biogas upgrading plant, economic data.

Characteristics	Value	Source
Base year	2016	
Fuel	Electricity	Sun et al. (2015)
Avoided CO_2	Not applicable: decarbonisation occurs in combustion in utilities	
Capacity	100 – 2,000 Nm^3/hour (creating green gas from raw biogas)	SGC (2013)
Efficiency	95 – 97%	Sun et al. (2015)
Lifetime	20 years	Lorenzi, Gorgoroni, Silva, & Santarelli (2019)
CAPEX	1,529 – 5,607 EUR_{2017}/(Nm^3/hour)	SGC (2013)
Fixed OPEX	31 – 280 EUR_{2017}/(Nm^3/hour)/year	Assumed 2-5% of CAPEX
Variable OPEX	4 – 19 EUR_{2017}/GJ (import of raw biogas)	IRENA (2017)
TRL	9	
Market entry	Present	

4.1.3 Electricity

Currently both steam and oil are used as heat transfer agents at Indorama Rotterdam, and they both can be heated with electricity instead of natural gas. An electric boiler could replace the natural gas boiler (VNP, 2018), while an electric thermal oil heater could replace the natural gas thermal oil heater (Pirobloc, n.d.-b). Both technologies use the resistance of an electric component to generate heat, and are commercially available. While electric thermal fluid heaters are commercially available, no data was available to make a techno-economic comparison to the conventional technology. Table 11 summarize the techno-economic data for an electric boiler.

Switching to electrified heat generation would require an increase in Indorama's purchase of electricity from the grid. At a system level, such a switch could have an impact on total greenhouse gas emissions, depending on the emissions intensity of electricity in the grid, and the effects of the increased demand on grid operations. Scope 2 emissions (from purchased electricity, heat, steam, or cooling) should be considered from a system perspective, though the table below considers only Scope 1 emissions (from on-site fuel combustion and processes).

Table 11. Electric boiler, economic data.

Characteristics	Value	Source
Base year	2016	
Fuel	Electricity (green, grid)	
Avoided CO_2	35.2 kt (28% of 2016 level)	See Table 4
Capacity	0.6 – 74 MWth (steam output)	Berenschot, Energy Matters, CE Delft, & Industrial Energy Experts (2017); Marsidi (2019); Thermona (2010); Weil-McLain (2016)
Efficiency	95 – 100%	Thermona (2010); Weil-McLain (2016)
Lifetime	10 – 15 years	Berenschot, CE Delft, & ISPT (2015); VNP (2018)
CAPEX	150 – 200 EUR_{2017}/kWth (including installation, steam output)[7]	Berenschot, Energy Matters, CE Delft, & Industrial Energy Experts (2017); Thermona (2010); Weil-McLain (2016)
Fixed OPEX	1.1 – 1.2 EUR_{2017}/kWth/year (steam output)	Berenschot, Energy Matters, CE Delft, & Industrial Energy Experts (2017); Thermona (2010); Weil-McLain (2016)
TRL	9	
Market entry	Present	

4.1.4 Hydrogen

Using hydrogen as a fuel would require a replacement of the natural gas burners of the boiler and thermal oil heater with hydrogen burners (VNP, 2018). In order for this option to support decarbonisation, hydrogen from low-carbon sources (often called green and blue hydrogen) need to be used. Green hydrogen is hydrogen which is produced from fossil carbon-free sources, such as biomass or renewable electricity (GeoPura, n.d.). Blue hydrogen is produced via steam methane reforming with carbon capture and storage (Van Capellen, Croezen, & Rooijers, 2018). Hydrogen requires different combustion conditions compared to natural gas, which means that additional changes to equipment and operation practices are needed. Table 12 gives the economic data of the hydrogen option. Although hydrogen technology is mature, the availability of low-cost, low-carbon hydrogen is a limiting factor to the implementation of the option. Furthermore, impacts on Scope 2 and 3 emissions (beyond the plant’s on-site combustion emissions) should be considered.

---

[7] Installation costs are site-specific.

Table 12. Retrofitting a hydrogen burner to the boiler, economic data.

Characteristics	Value	Source
Base year	2016	
Fuel	Hydrogen (green or blue)	
CO_2-eq avoided	35.2 kt (28% of 2016 level)	See Table 4
Capacity	1 – 85 MWth	E&M Combustión (2019)
Efficiency	100% (LHV) 85% (HHV)	VNP (2018)
Lifetime	20 years	VNP (2018)
CAPEX	246 EUR_{2017}/kWth (hydrogen burners, including installation, steam output)	VNP (2018)
Fixed OPEX	5 – 12 EUR_{2017}/kWth/year (hydrogen burners, steam output)	Assumed 2-5% of CAPEX
TRL	9	
Market entry	Present	

4.2 Heat recovery and utilization

PX oxidation produces 7.62 GJ of heat per tonne of PTA production and bottle-grade PET production also produces residual heat, mostly originating from its cooling processes. Currently, much of the residual heat is removed with cooling water. Recovering and utilizing this heat in the process would reduce overall energy needs and could contribute to decarbonisation. Incorporating the flow of cooling water into a heat network could recover the residual heat which is transported by the cooling water. There are multiple possible destinations for this heat, but this is limited by the quality of the residual heat. The provided temperature of the residual heat and the availability of the recovered heat are crucial for implementation of this option.

The residual heat could contribute to meeting the heat demand for bottle-grade PET and PTA production, which would require additional equipment and infrastructure at Indorama Rotterdam. The recovered heat could be used to decrease the fuel demand for both oil and steam heating. Techno-economic data for the required equipment is site-specific and not available publicly.

Mechanical vapour recompression is a technology which increases the temperature of vapour by performing mechanical compression (Marsidi, 2018). This technology could allow Indorama Rotterdam to produce useful temperatures from the residual heat which is already produced on site. Table 14 gives the economic data of installing mechanical vapour recompression technology at the site.

Table 13. Mechanical vapour recompression, economic data.

Characteristics	Value	Source
Fuel	Residual heat and electricity	
Avoided CO_2	Savings through less energy consumption	
Capacity	4 – 20 MWth	Marsidi (2018)
Efficiency	COP: 3.5 – 10	Klop (2015)
Lifetime	10 years	Marsidi (2018)
CAPEX	268 – 612 EUR_{2017}/kWth	Marsidi (2018)
Fixed OPEX	8 – 18 EUR_{2017}/kWth/year	Marsidi (2018)
TRL	9	
Market entry	Present	

Recovered excess heat from the process could also be transported to off-site locations for use in the built environment or horticulture sectors (Port of Rotterdam, 2019a), providing additional revenue and helping to decarbonise other sectors. Currently, Indorama is not connected to the heat network of the Port of Rotterdam; to make the sale of residual heat more feasible, the existing heat network would need to be expanded. An expansion plan for the heat network of the Port of Rotterdam already exists, but it is not clear if Indorama Rotterdam will be connected. The CAPEX of installing a heat network is given by Figure 19. Table 13 gives the economic data of installing a heat network at the site.

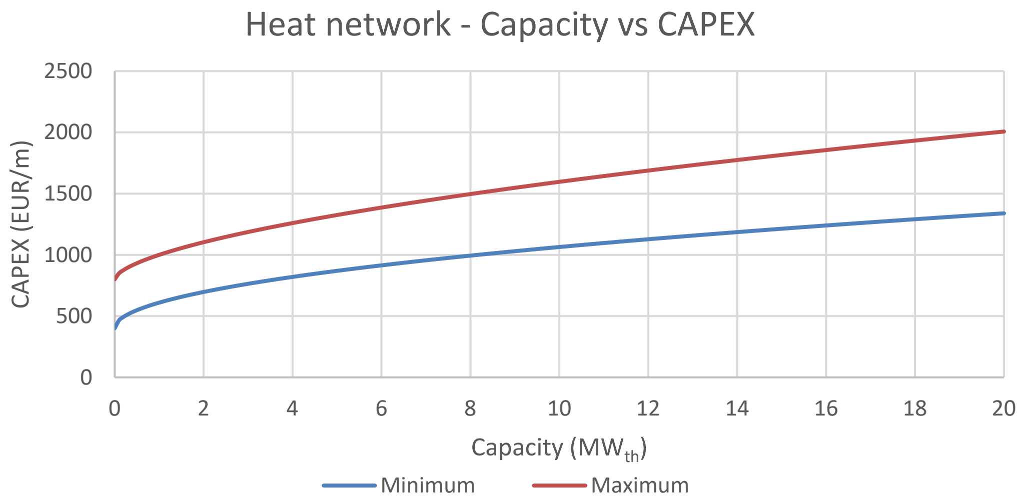

Figure 16. CAPEX for installing a heat network as a function of capacity.

Source: CE Delft (2019)

Table 14. Heat network, economic data.

Characteristics	Value	Source
Fuel	Residual heat	
Avoided CO_2	Savings through less energy consumption	
Capacity	No theoretical limit	
Efficiency	1% heat loss per km	Assumed by Kapil, Bulatov, Smith, & Kim (2012)
Lifetime	20 years	Kavvadias, & Quoilin (2018)
CAPEX	Depends on capacity, minimum of 383 EUR_{2017}/m (heat pipeline)	CE Delft (2019)
Fixed OPEX	Depends on capacity, minimum of 8 EUR_{2017}/m/year (heat pipeline)	Assumed 2-5% of CAPEX
TRL	9	
Market entry	Present	

4.3 Process substitution

Alternative processes could also reduce the emissions impact of production. For bottle-grade PET production at Indorama Rotterdam, there are two types of technologies for both melt polymerization (GPT and INVISTA) and solid state polymerization (GPT and Buhler). It is also possible to produce bottle-grade PET directly from PX, rather than first producing PTA, via a process developed by GPT (GPT, n.d.). Indorama Rotterdam could consider transitioning to full production with the technology configuration which provides the site with the highest energy efficiency. Relative energy intensities of these processes were not available publicly.

Investment costs of new equipment are a limiting factor for the process substitution option. Investment decisions typically come at the end of the existing equipment's lifetime, when the company decides to reinvest and refurbish or build new equipment; this window of opportunity could be used to upgrade, if needed, to the most efficient commercially available technology.

4.4 Recycling

Recycling not only reduces environmental contamination and the use of limited resources, but from the perspective of the whole value chain also reduces the energy consumption and CO_2 emissions from PET production (ACS Sustainable Chem. Eng., 2018). PET has become popular in part because it is theoretically completely recyclable. However, the European recycling rate of PET packaging was only 48.3% in 2016 (Plasteurope, 2017). The recycling rate of PET is limited by technical, economic and social factors. The remainder is combusted, along with other waste streams, to generate electricity or heat, or discarded in a landfill or the environment.

The recycling rate of PET in the Netherlands is highly dependent on government policies (Stichting Ons Statiegeld, n.d.). With the deposit-return scheme in the Netherlands, about 95% of the large PET bottles purchased in the Netherlands (larger than 0.5 L) are collected for recycling, which accounted for about 26.5 kt of recycled PET plastic in 2017 (Snijder, & Nusselder, 2019). In the Netherlands, this programme does not yet cover small PET bottles (up to 0.5 L), for which the recycling rate is only 58% (Statiegeldalliantie, 2019). These will be included in the programme starting on 1 July 2021, with the aim of increasing collection rates (Rijksoverheid, 2020). The Dutch recycling rate of all plastic packaging mass was around 47.5% in 2017, while the remaining 52.5% was burned for energy production (Snijder, & Nusselder, 2019). PET is also used in other types of packaging, which do not have special collection schemes; the recycling rate for these other products is around 47.5%.

Mechanical recycling

Mechanical recycling involves cutting discarded PET bottles into small pieces (rPET flakes), which are then blended with virgin PET pellets in the production of fibers. The mechanical recycling of PET bottles into flakes results in low IVs, and this degradation makes it impossible to produce PET pellets from rPET flakes. Virgin PET needs to be added to obtain the required IV; the maximum share of rPET flakes in the total input is 35% (ACS Sustainable Chem. Eng., 2018).

Because mechanical recycling of PET lowers its IV, bottle-grade PET is typically recycled into fiber-grade PET. The degradation in quality of recycled PET makes it difficult to make this sector truly circular. The additives which give colour to PET bottles makes recycling into new bottles problematic, because the additives are difficult to remove in the recycling process, making it difficult to manufacture transparent bottles from recycled PET. If recovered post-consumer PET is contaminated with other types of material, then the quality decreases significantly and the process required to sort and recycle the PET becomes more complex and costly. As PET is often used for food packaging, food safety standards and regulations can also complicate the recycling process (Snijder, & Nusselder, 2019).

IVL committed to increasing its global rPET production capacity to 750 kt/year by 2025, in order to further develop circular PET value chains. IVL acquired Wellman International, with recycling facilities in Spijk (NL) and Verdun (FR) in 2011, and Sorelpa (FR) in 2018 (ICIS, 2020).

Depolymerization

Since April 2018, IVL has also been working with Ioniqa (Eindhoven), a company which uses chemical recycling to completely convert PET waste into recycled bis(2-hydroxyethyl) terephthalate (BHET), the tradeable monomers of PET (Ioniqa, n.d.-a). Unlike mechanical recycling, chemical recycling depolymerizes the chemical structure of PET into BHET, which can be used to produce PET pellets without the addition of any virgin materials (Larionova, 2019). Indorama Rotterdam recently received a permit to import BHET into the Netherlands to be used to produce PET pellets at their Rotterdam site (Provinciaal blad, 2019). According to a Life-Cycle Assessment (LCA) study by CE Delft, PET produced via depolymerization with the Ioniqa process results in slightly more greenhouse gas emissions than mechanically recycled PET, mainly because the production of recycled BHET requires more energy than the production of rPET flakes. However, this does not account for the fact that the quality of PET from recycled BHET is higher than PET from mechanically recycled materials. Both are far superior to virgin PET production from a lifecycle greenhouse gas emissions perspective, with the Ioniqa process resulting in 1-1.3 tCO_2-eq/t PET, mechanically recycled PET resulting in 0.6-0.9 tCO_2-eq/t PET, compared to nearly 4 tCO_2-eq/t PET from conventional production.[8] A multi-

---

[8] The assumptions about conventional PET production used in this LCA study may not be compatible with the production at Indorama Rotterdam. These emissions values cannot be compared to the described

cycle analysis shows that with additional cycles, the Ioniqa process has an emissions advantage over mechanical recycling because of the reduced losses and higher product quality (CE Delft 2018). As of summer 2019, Ioniqa has begun operating its self-built 10 kt/y plant in Geleen to recycle PET plastic into recycled BHET (Ioniqa, n.d.-b). No data was publicly available on specific energy consumption of the process, operating costs, efficiency, and equipment lifetimes.

Table 15. Magnetic depolymerization of PET, economic data.

Characteristics	Value	Source
Avoided CO_2	Life cycle savings from avoided virgin PET production and avoided incineration, depending on local waste management system and PET production process.	CE Delft (2018)
Capacity	50 kt BHET /year	CE Delft (2020)
CAPEX[9]	710 $MEUR_{2017}$/Mt BHET	CE Delft (2020)
TRL	8	CE Delft (2020)
Market entry	2025	CE Delft (2020)

4.5 MEG and PX from biomass

PET production requires MEG and PX as feedstocks, which currently are both primarily produced from crude oil. It is also possible to produce MEG and PX from biomass. Feedstock substitution would not reduce the direct CO_2 emissions of Indorama Rotterdam, but would have benefits upstream and downstream in the PET value chain, as absorption of CO_2 by the biomass needed to produce bio-feedstock would make the feedstock carbon neutral. In 2016, 20,000 tonnes of partially bio-based (27% on mass basis) PET were produced at Indorama Rotterdam using bio-MEG (CE Delft, 2017). As MEG is a by-product of biofuel production, bio-MEG is already available on a large scale. The production of partially bio-based PET is still far from the company's full PET production. The site has a lot of potential to increase the use of bio-MEG, but the price of bio-MEG limits this option. A CE Delft study found that the threshold oil price at which bio-based PET would become competitive with fossil-based PET is around 120 USD/barrel, in the absence of other incentives (CE Delft, 2017).

The concept of bio-PX exists, but the technology to produce it is not yet mature (CE Delft, 2017). A technically feasible production route for bio-PX has been developed, but the TRL is low (Gursel, Dijkstra, Huijgen, & Ramirez, 2019). Tables 15 and 16 give the economic data of importing bio-MEG and bio-PX. Because of its low TRL level, market price data for bio-PX was not available.

---

production process in earlier chapters, because they include life-cycle impacts, such as transport-related emissions and end-of-life incineration.

[9] Converted to EUR2017 from EUR2019.

Table 16. Bio-MEG imports, economic data.

Characteristics	Value	Source
Avoided CO_2	No direct decarbonization, effects seen on scope 3 emissions	
CAPEX	Storage capacity	
Price	1,190 – 1,281 EUR_{2017}/tonne (30 – 40% higher than fossil-based MEG)	Tecnon OrbiChem (n.d.)
TRL	9	CE Delft (2017)
Market entry	Present	CE Delft (2017)

Table 17. Bio-PX imports, economic data.

Characteristics	Value	Source
Avoided CO_2	No direct decarbonization, effects seen on scope 3 emissions	
CAPEX	Storage capacity	
TRL	1-3	
Market entry	2040	

4.6 Carbon Capture and Storage (CCS)

The Port of Rotterdam has the ambition to install CO_2 transport and storage infrastructure through the Porthos project (Port of Rotterdam, 2019b). The open access transport and storage infrastructure will connect the Port of Rotterdam to a CO_2 storage location under the North Sea, with injection beginning in 2024. Indorama Rotterdam would need CO_2 capture equipment in order to utilize this infrastructure.

There are four major types of CO_2 capture: post-combustion, pre-combustion, oxyfuel combustion, and chemical looping combustion (Leung, Caramanna, & Maroto-Valer, 2014). For Indorama Rotterdam, the direct CO_2 emissions of the CHP could most feasibly be captured with amine scrubbing post-combustion CO_2 capture technology (Ter Telgte, 2012). This is an end of pipe technology that can be retrofitted to existing equipment. Combining CO_2 capture with biomass fuels, which are discussed in Sections 4.1.1 and 4.1.2, would lead to negative CO_2 emissions. Table 17 gives the economic data of retrofitting the CHP with CO_2 capture technology.

Table 18. CHP with amine scrubbing (post-combustion capture), economic data.

Characteristics	Value	Source
Fuel	Steam and electricity	
Capture rate	85 – 90%	Ter Telgte (2012)
Direct CO_2 savings	16.8 – 17.8 kt (13 – 14% of 2016 level)	See Table 4
Lifetime	25 years (assumed to be same as CHP)	IEA (2010b); Ter Telgte (2012)
CAPEX	58 – 68 EUR_{2017}/ tCO_2 capture capacity	Ter Telgte (2012)
Fixed OPEX	2.3 – 2.7 EUR_{2017}/tCO_2 capture capacity /year (CO_2 captured)	Ter Telgte (2012)
TRL	9	
Market entry	Carbon capture technology is available, but transport and storage infrastructure is not yet present in the Port of Rotterdam.	

4.7 Product design

The way a plastic product is designed has a significant influence on its recyclability (ING, 2019). Simpler designs are more easily recyclable; using one type of plastic and one color per product is beneficial for recycling. Mixing plastic with other packaging types, such as cardboard, increases the complexity and cost of sorting, separating, and recycling post-consumer waste.

PET packaging can be designed in a way that requires less PET pellets for the same function. There is already a trend towards decreased PET per packaging product on a mass basis, driven by cost reductions. For example, between 1970 and 2015, a plastic Spa bottle has become around 50% lighter (ING, 2019).

Reheat additive in PET pellets can decrease the energy consumption of molding pellets into bottles with 38% (PlasticsToday, 2012), but using reheat PET is not always desired by bottle manufacturers, because it decreases the transparency of the PET plastic.

Product design could be leveraged to reduce emissions from PET production, but would require action on the part of many actors in the value chain, including consumers, product designers, packaging manufacturers, recycling companies, and potentially even logistics companies. Full supply chain circularity holds potential to deliver significant emissions reductions, but insufficient data is available to quantify the costs or potentials.

4.8 Alternative materials

Plastics from bio-based feedstock are not necessarily bio-degradable (CE Delft, 2017). PET produced from bio-MEG and bio-PX, for example, has the same properties as PET produced from fossil MEG and PX, including low biodegradability. Some alternative materials made from biomass are both bio-based and bio-degradable, such as PLA (polylactic acid). Replacing fossil plastics with biobased plastics mainly decreases the downstream emissions of the value chain, at the end of final product lifetimes.

Avantium, a company based in Amsterdam, specializes in the production of PEF (polyethylene 2,5-furandicarboxylate), which is a bio-based plastic without biodegradability (Food Packaging Forum, 2013). PEF could act as a substitute for PET (Avantium, n.d.). PEF has identical recycling properties as PET, but mixing of plastic types would still need to be avoided to make recycling more efficient and cost-effective (KIDV, 2017). The PEF production process is similar to the PET production process, but it substitutes FDCA (2,5-furandicarboxylic acid), which is bio-based, for PTA. The MEG is produced from biomass.

PET plastic in some applications can also be replaced with non-plastic materials, such as cardboard, aluminum or glass. This substitution can have advantages and disadvantages, depending on the material, application, and supporting infrastructure. Life cycle analysis for specific applications and materials is needed to assess the effects of substituting these materials on greenhouse gas emissions throughout the value chain, energy consumption, water consumption, and other environmental impacts.

5 Discussion

In the previous chapters, a broad range of options have been outlined to decarbonize PTA and bottle-grade PET production in the Netherlands. All have advantages and disadvantages which are important to consider. The fuels, feedstocks, and intermediate products used by this sector (such as natural gas, paraxylene, MEG, and PTA) are internationally traded commodities, whose prices can fluctuate, making the optimal decarbonisation strategy in years to come difficult to predict. Long technology lifetimes in this sector could lead to lock-in of higher-emissions processes, so efforts to decarbonise should take into account investment cycles in the industry. Many of the technologies described here could play a role in the decarbonisation of this sector; the competitiveness of each will depend on external factors beyond the bottle-grade PET sector.

In the short term, there are some energy efficiency gains which can be immediately implemented, mainly via optimization and adjustment of equipment and operations. Several existing policies target improvements in this area. While the energy and emissions savings from such energy efficiency improvements should not be neglected, these incremental savings will not lead to full decarbonisation of Dutch industry in the long-term, and should be considered as short-term gains as part of the transition to a lower-carbon economy.

Full electrification of the process, including process heat, would eliminate all direct Scope 1 emissions from the site. Several challenges could limit the applicability and sustainability of this option. Availability of low-carbon electricity is crucial to ensuring that electrification reduces emissions at the system level, and not only on the site. Scope 2 emissions, from purchased heat and electricity, are not shown in this report, but long-term decarbonization pathways for the Dutch industrial sector must take into account system-level effects and the impacts of technology choices on global emissions. If in the future, many end-users compete for limited low-carbon electricity, this could lead to higher prices, making electrification a costly option, and could potentially shift emissions to another part of the economy. In addition, an increase in electricity demand based on electrification in all end-use sectors, from the built environment to transport to electricity, could put pressure on the Dutch grid, and would require improved infrastructure planning and management tools for a larger, more complex grid. These future developments in electricity markets and grid management, in combination with energy taxation schemes, both in the Netherlands and more broadly in Europe, will determine the cost of electricity in the future, and thus the viability of electrification in this sector. Despite the challenges, the continuing trend of falling costs for low-carbon electricity generation, as well as electrified end-use technologies, such as heat pumps, could quickly change the picture and improve the prospects for electrification.

Other fuel substitution options have the potential to reduce emissions as well; biogas, green gas, and hydrogen fuel could allow Indorama’s process to continue without fundamental changes, while eliminating emissions from heat generation. The ease of a transition from natural gas to another gaseous fuel is a significant advantage. However, these options also face similar uncertainties related to the sustainable potentials and future markets. Biogas and green gas supply is dependent on limited sustainable biomass resources, and demand in other industrial sectors and for the built environment may also increase. Hydrogen could be generated with low carbon emissions from low-carbon electricity or from natural gas with CCS, but the availability at a reasonable cost will also be constrained by competition with demands for other applications, infrastructure and planning constraints, and market forces.

Carbon capture and storage under the North Sea is also a technically feasible candidate in this case; the planned Porthos project infrastructure will pass nearby the Indorama Rotterdam site. This option, like the others, must be considered in the context of the future energy system and policy framework. Post-combustion capture is commercially available, but the economic feasibility in the long run for a relatively small utility and the competitiveness with other emissions reduction options given the additional energy demand and infrastructure costs, is uncertain.

Traditional mechanical recycling of PET bottles to rPET flakes reduces the impact of PET production significantly in energy and emissions terms. However, it has some important limitations. Degradation in the quality of recycled PET means that this cannot be a fully circular recycling loop. The share of rPET in a product has a technical limit of about 35%. Depolymerization, or chemical recycling, could resolve some of quality problems associated with mechanical recycling, but it is still at an early stage.

While there are both technical and practical limits to the potential to increase recycling rates for plastic packaging, researchers from Wageningen University estimate that with a radically improved system at the design, sorting, collection, and recycling steps, the Netherlands could technically reach a 72% net plastic packaging recycling rate (Brouwer et al., 2020). Improving the system along the whole value chain from "cradle to grave" would unlock greater benefits in combination with improved recycling and production. Improving collection and sorting, both via behavioral change (for example, by extending the deposit scheme to smaller PET bottles), and via technical solutions (for example, improvements in automated sorting machines) would have a great impact on the circularity of the sector and the life cycle emissions of PET products. Designing products to be recycled would also greatly improve the efficacy of the recycling system. This could mean designing products with fewer different polymer types and colors, and fewer, easier-to-separate elements, and making products more easily recognized by automated sorting machines.

More fundamental shifts in the structure of the packaging industry would also have a strong impact on the emissions and activities of the bottle-grade PET sector. Looking beyond the limits of PET production facilities, bottles and other packaging could be produced with recycled PET or with alternative materials. New materials, including bio-based alternatives to PET, as well as existing materials such as cardboard and glass, are all being explored. Many companies are already producing bottles with less material than in the past. These shifts may be driven by market demand for alternatives, by technological improvements that lead to competitive new options, by regulatory measures, or more likely, by a combination of these.

Many factors beyond the plant fence will affect the future of this sector, from infrastructure availability, to consumer preferences and behaviors, to energy and commodity market developments, to European and Dutch policies for industry, energy and waste management. The exploration in this report of existing decarbonization options for bottle-grade PET production does not offer a single solution. The transition to a low-carbon economy will require many changes in the operations of the industrial sector and the energy system. Decarbonization options should be considered in the context of broader shifts in energy markets and energy policy, and their effects at the site, sector, and global level taken into account. Any pathway will require investments in new technologies or capabilities, and no one strategy will fit all scenarios and sites. Indorama Rotterdam's decarbonisation pathway may differ from bottle-grade PET producers elsewhere, and from other industrial sites across the Netherlands.

References

ACS Sustainable Chem. Eng. (2018), 6, 9725-9733.

Alm, P., Falk, K., Nightingale, T., & Zehr, Z. (2011). Sleeman biogas boiler system design. *Studies by Undergraduate Researchers at Guelph*, 5(1), 63-68.

Avantium. (n.d.). What we do - Renewable Polymers. Retrieved November 28, 2019 from https://www.avantium.com/business-units/renewable-polymers

Bailon Allegue, L., & Hinge, J. (2014). Biogas upgrading – Evaluation of methods for H_2S removal.

Berenschot, CE Delft, & ISPT. (2015). Power to products.

Berenschot, Energy Matters, CE Delft, & Industrial Energy Experts. (2017). Electrification in the Dutch process industry.

Bharathiraja, B., Sudharsana, T., Jayamuthunagai, J., Ramanujam, P. K., Sivasankaran, C., & Iyyappan, J. (2018). Biogas production – A review on composition, fuel properties, feed stock and principles of anaerobic digestion. *Renewable and Sustainable Energy Reviews*.

Bork, H. (2020). New PTA Production Plant into Operation. Retrieved March 17, 2021 from https://www.process-worldwide.com/new-pta-production-plant-into-operation-a-949738/.

Brouwer, M. T., van Velzen, E. U., Ragaert, K. and ten Klooster, R. (2020). Technical Limits in Circularity for Plastic Packages. *Sustainability* (12), doi:10.3390/su122310021.

Cao, N., Chang, E., & Kaufman, M. (2011). New Terephthalic Acid Process. *Senior Design Reports (CBE).* 24. https://repository.upenn.edu/cgi/viewcontent.cgi?article=1027&context=cbe_sdr

CBS. (2020). Business survey Netherlands; quarterly, to sector/branches.

CE Delft. (2017). Biobased Plastic in a Circular Economy.

CE Delft. (2018). Samenvatting LCA Ioniqa : Screening carbon footprintanalyse.

CE Delft. (2019). Overzicht aanpassingen Vesta MAIS. Retrieved January 10, 2020 from https://www.rvo.nl/sites/default/files/2019/07/CE%20Delft%20Overzicht%20aanpassingen%20Vesta%20MAIS%20Def.pdf

CE Delft. (2020). CO2-redutie met de Circular Biobased Delta: Aanzet voor een routekaart voor de periode tot 2030.

ChemicalBook. (n.d.). Terephthalic Acid Bis(2-hydroxyethyl) Ester. Retrieved January 14, 2020 from https://www.chemicalbook.com/ProductDetail_EN_768687.htm

ChemistryScore. (n.d.). Esterification. Retrieved August 20, 2019 from https://www.chemistryscore.com/esterification

Coca-Cola Nederland. (2017, October 18). Drie vragen over Coca-Cola, plastic en PET. Retrieved August 6, 2019 from https://www.cocacolanederland.nl/stories/drie-vragen-over-coca-cola-plastic-en-pet

CPME. (n.d.). CPME Members. Retrieved October 17, 2019 from https://www.cpme-pet.org/members

CPME. (2016). Purified Terephthalic Acid (PTA). *PlasticsEurope*.

CPME. (2017). Polyethylene Terephthalate (PET) (Bottle Grade). *PlasticsEurope*.

Danish Energy Agency. (2017). Technology Data - Renewable fuels. Retrieved January 7, 2020 from https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf

De Volkskrant. (1995, July 19). Komst Eastman levert Europoort 300 banen op. Retrieved September 19, 2019 from https://www.volkskrant.nl/nieuws-achtergrond/komst-eastman-levert-europoort-300-banen-op~b23bec66

De Volkskrant. (1996, June 20). Eastman Chemical wil zes fabrieken in Europoort. Retrieved August 14, 2019 from https://www.volkskrant.nl/nieuws-achtergrond/eastman-chemical-wil-zes-fabrieken-in-europoort~b00f2ead

Echemi.com. (2020). Isophthalic acid Price Analysis. Retrived on 20 February 2020 from https://www.echemi.com/productsInformation/pid_Seven3373-isophthalicacid.html.

EEA. (2019). Reported data on large combustion plants covered by the Industrial Emissions Directive (2010/75/EU). Retrieved October 1, 2019 from https://www.eea.europa.eu/data-and-maps/data/lcp-9

E&M Combustión. (2019, July 14). E & M Combustion develops a hydrogen burner for a chemical plant in Portugal. Retrieved September 24, 2020 from https://emcombustion.es/en/hydrogen-burner

Engineering ToolBox. (2003a). Air - Composition and Molecular Weight. Retrieved September 23, 2019 from https://www.engineeringtoolbox.com/air-composition-d_212.html

Engineering ToolBox. (2003b). Fuels - Higher and Lower Calorific Values. Retrieved June 30, 2020 from https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

Essent. (n.d.). Gasproducten en gasprijzen. Retrieved November 27, 2019 from https://www.essent.nl/kennisbank/stroom-en-gas/energiebronnen/gasproducten-gasprijzen

European Commission. (2016a). Case M.7918 - Indorama Netherlands/Guadarranque Polyester. Retrieved September 26, 2019 from https://ec.europa.eu/competition/mergers/cases/decisions/m7918_270_3.pdf

European Commission. (2016b). Mapping and analyses of the current and future (2020 – 2030) heating/cooling fuel deployment (fossil/renewables). Work package 2: Assessment of the technologies for the year 2012.

Farah, S., Kunduru, K. R., Basu, A., & Domb, A. J. (2015). Molecular Weight Determination of Polyethylene Terephthalate. *Poly(Ethylene Terephthalate) Based Blends, Composites and Nanocomposites*, William Andrew Publishing, 143-165. doi: 10.1016/B978-0-323-31306-3.00008-7

Food Packaging Forum. (2013, November 19). PEF: New food contact polymer on the horizon. Retrieved February 26, 2020 from https://www.foodpackagingforum.org/news/pef-new-food-contact-polymer-on-the-horizon

General Electric. (n.d.). LM2500 Power Plants - 50 Hz. Retrieved October 31, 2019 from https://www.ge.com/content/dam/gepower/global/en_US/documents/gas/gas-turbines/aero-products-specs/lm2500-50hz-fact-sheet-product-specifications.pdf

GeoPura. (n.d.). What is Green Hydrogen? And Why Should We Start Using It In 2019? Retrieved January 8, 2020 from https://www.geopura.com/blog/why-we-should-start-using-green-hydrogen-in-2019

Gigler, J. and Weeda, M. (2018). Outlines of a Hydrogen Roadmap. TKI Nieuw Gas, Topsector Energie.

GPT. (n.d.). IntegRex Technology. Retrieved January 10, 2020 from http://integrex-tech.com/index.html

Griffin, P., Hammond, G. and Norman, J. (2015). Industrial Energy Use (UK). Retrieved January 10, 2020 from https://ukerc.rl.ac.uk/DC/cgi-bin/edc_search.pl.

Gupta, V. B. and Bashir, Z. (2002). *Handbook of Thermoplastic Polyesters*. Fakirov, S. (ed.), chapter 7, 320. Wiley-VCH, Weinheim, ISBN 3-527-30113-5.

Gursel, I. V., Dijkstra, J. W., Huijgen, W. J. J., & Ramirez, A., (2019). Techno-economic comparative assessment of novel lignin depolymerization routes to bio-based aromatics. *Biofuels. Bioprod. Bioref*, 13, 1068-1084. doi: 10.1002/bbb.1999

HDIN Research. (2019). Purified Terephthalic Acid (PTA) Production Capacity reach to 83.8 Million Tons in 2018. Retrieved March 16, 2021 from https://www.hdinresearch.com/news/33.

Heattec. (n.d.). Bentone Biogas Burner BG700-2 300-1200 KW. Retrieved January 15, 2020 from https://www.heattec-webshop.com/bentone-biogas-burner-bg700-2-300-1200-kw

Helmke, R. (2014, April 8). The Thermoforming Process. Retrieved August 21, 2019 from https://www.plasticingenuity.com/blog/common-plastics-for-thermoforming

HIER. (2017, July 29). Op deze plekken in Nederland gebruiken we al biogas. Retrieved November 22, 2019 from https://www.hier.nu/themas/stroom-en-gas/op-deze-plekken-in-nederland-gebruiken-we-al-biogas

ICIS. (2018). rPET Meeting. Retrieved October 24, 2019 from https://textileexchange.org/wp-content/uploads/2018/11/TE_rPET_Round_Table_Milan_2018-Slides.pdf

ICIS. (2020). Indorama to Increase PET Recycling Capacity to 750 000 Tonnes/Year by 2025. Retrieved March 17, 2021 from https://www.icis.com/explore/resources/news/2020/04/16/10497024/indorama-to-increase-pet-recycling-capacity-to-750-000-tonnes-year-by-2025.

IEA. (2010a). Industrial Combustion Boilers.

IEA. (2010b). Combined Heat and Power.

IEA. (2020). Outlook for biogas and biomethane: prospects for organic growth. *World Energy Outlook Special Report.*

Indiamart. (n.d.). Powder Purified Terephthalic Acid. Retrieved September 19, 2019 from https://www.indiamart.com/proddetail/purified-terephthalic-acid-11146627597.html

Indorama Ventures. (n.d.-a). Indorama Ventures Europe B.V. - PET. Retrieved August 5, 2019 from https://www.indoramaventures.com/en/worldwide/783/indorama-ventures-europe-bv-pet

Indorama Ventures. (n.d.-b). Indorama Ventures Europe B.V. - PTA. Retrieved August 7, 2019 from https://www.indoramaventures.com/en/worldwide/764/indorama-ventures-europe-bv

Indorama Ventures. (n.d.-c). Our Products - Netherlands. Retrieved August 8, 2019 from https://www.indoramaventures.com/en/product/finder?family_id=&group_id=&specification_id=&location_id=13

Indorama Ventures. (n.d.-d). Indorama Ventures Polymers Germany GmbH. Retrieved September 25, 2019 from https://www.indoramaventures.com/en/worldwide/1284/indorama-ventures-polymers-germany-gmbh.

Indorama Ventures. (n.d.-e). UAB Orion Global PET. Retrieved September 25, 2019 from https://www.indoramaventures.com/en/worldwide/907/uab-orion-global-pet

Indorama Ventures. (n.d.-f). About our Products. Retrieved October 3, 2019 from https://www.indoramaventures.com/en/our-products/at-a-glance

Indorama Ventures. (n.d.-g). Wellman International Limited. Retrieved October 3, 2019 from https://www.indoramaventures.com/en/worldwide/818/wellman-international-limited

Indorama Ventures. (n.d.-h). Technical Datasheet RAMAPET N180. Retrieved October 4, 2019 from https://plasticker.de/recybase/docs/27055_1463559873.pdf

Indorama Ventures. (n.d.-i). Technical Datasheet RAMAPET P184. Retrieved October 7, 2019 from https://materials.ulprospector.com/en/profile/odm?tds&docid=122690

Indorama Ventures. (n.d.-j). Company at a Glance. Retrieved October 17, 2019 from https://www.indoramaventures.com/en/our-company/at-a-glance

Indorama Ventures. (2011). Indorama Ventures Public Company Limited and its Subsidiaries. Retrieved September 18, 2019 from http://capital.sec.or.th/webapp/corp_fin/datafile/FS/2010/031220101126E03.DOC

Indorama Ventures. (2017a). PTA - Sales Specification. Retrieved September 23, 2019 from https://www.indoramaventures.com/storage/downloads/product/feedstock/pta/Indorama-Ventures-Europe-Netherland.pdf

Indorama Ventures. (2017b). IVL PET Production EN Version. Retrieved September 26, 2019 from https://www.youtube.com/watch?v=rLOUxxwaXuA

Indorama Ventures (2020). Indorama Ventures Announces 2019 Results. Retrieved 9 March 2021 from https://www.indoramaventures.com/en/updates/earnings-release/1385/indorama-ventures-announces-2019-results#:~:text=Indorama%20Ventures%20has%20approx.,US%24%2011.4%20billion%20in%202019.

ING. (2019). Plastic verpakkingen in de voedingssector. Retrieved November 20, 2019 from https://www.ing.nl/media/ING_EBZ_de-plastic-puzzel-in-de-voedingssector_tcm162-180782.pdf

INVISTA. (n.d.). Polymer Technology Description. Retrieved February 19, 2020 from https://ipt.invista.com/en/products/Polyester-Value-Chain/product-information/Polymer

Ioniqa. (n.d.-a). Partnerships. Retrieved November 27, 2019 from https://ioniqa.com/partnerships

Ioniqa. (n.d.-b). Ioniqa's Circular Solution. Retrieved November 28, 2019 from https://ioniqa.com/applications

IRENA. (2017, March 6). Biogas Cost Reductions to Boost Sustainable Transport. Retrieved January 7, 2020 from https://www.irena.org/newsroom/articles/2017/Mar/Biogas-Cost-Reductions-to-Boost-Sustainable-Transport

Kapil, A., Bulatov, I., Smith, R., & Kim, J. (2012). Process integration of low grade heat in process industry with district heating networks. *Energy*, 44(1), 11-19. doi: 10.1016/j.energy.2011.12.015

Kavvadias, K. C., & Quoilin, S. (2018). Exploiting waste heat potential by long distance heat transmission: Design considerations and techno-economic assessment. *Applied Energy*, 216, 452-465. doi: 10.1016/j.apenergy.2018.02.080

KIDV. (2017). De invloed van PEF op de PET-recycling. Retrieved February 26, 2020 from https://www.kidv.nl/7213/de-invloed-van-pef-op-de-pet-recycling.html

Klop, E. (2015). Steaming ahead with MVR. *COSPP*. Retrieved January 15, 2020 from https://blueterra.nl/wp-content/uploads/2018/03/Steaming-ahead-with-MVR-COSPP.pdf

Köpnick, H. , Schmidt, M. , Brügging, W. , Rüter, J., & Kaminsky, W. (2000). Polyesters. *Ullmann's Encyclopedia of Industrial Chemistry*, (Ed.), 11-12. Wiley-VCH. doi: 10.1002/14356007.a21_227

Kreijkes, M. (2017). Looking under the hood of the Dutch energy system. Retrieved August 13, 2019 from https://www.clingendaelenergy.com/inc/upload/files/CIEP_2017___01_Looking_under_the_hood_of_the_dutch_energy_system.pdf

Kvist, T. (2011). Establishment of a biogas grid and interaction between a biogas grid and a natural gas grid.

Larionova. A. (2019, April 9). DuPont Teijin Films launches PET chemical recycling process. *MRC*. Retrieved January 14, 2020 from http://www.mrcplast.com/news-news_open-351533.html

Leung, D. Y. C., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*, 39, 426-443. doi: 10.1016/j.rser.2014.07.093

Levi, P. G., & Cullen, J. M. (2018). Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products. Department of Engineering, University of Cambridge, Cambridge.

Lorenzi, G., Gorgoroni, M., Silva, C., & Santarelli, M. (2019). Life Cycle Assessment of biogas upgrading routes. *Energy Procedia*, 158, 2012-2018. doi: 10.1016/j.egypro.2019.01.466

Lukkes. (n.d.). Industrie bundelt krachten en spreidt risico's. Retrieved February 19, 2020 from http://www.lukkes.com/pdfs/petrochem.pdf

Marjolaine. (2017, December 6). Interest in biogas CHP. Retrieved January 8, 2020 from https://www.biogasworld.com/news/biogas-chp-discover-technologies/

Marsidi, M. (2018, May 28). Technology Factsheet – Industrial Mechanical Vapour Recompression (MVR). *Energy.nl*. Retrieved January 9, 2020 from https://energy.nl/wp-content/uploads/2019/06/Industrial-mechanical-vapour-recompression-1.pdf

Ma, Y. (2005). Post polymerization of polyester for fiber formation. Eindhoven: Technische Universiteit Eindhoven. doi: 10.6100/IR590790

MCPI. (2018). MCPI Project Report Proposed Expansion of PTA manufacturing capacity by setting up a plant of 1.25 MTPA capacity. Retrieved September 24, 2019 from http://www.environmentclearance.nic.in/writereaddata/Online/TOR/25_Jul_2018_1858422437A1T41X5PROJECTREPORT.pdf

Murray, C. (2010, May 13). Indorama to almost double capacity at Dutch PET site by 2012. *ICIS News*. Retrieved September 18, 2019 from https://www.icis.com/explore/resources/news/2010/05/13/9358952/indorama-to-almost-double-capacity-at-dutch-pet-site-by-2012

Murray, C. (2018, June 7). Europe PET price soars 30% in first five months of 2018 on unprecedented tightness. *ICIS News*. Retrieved October 15, 2019 from https://www.icis.com/explore/resources/news/2018/06/07/10228791/europe-pet-price-soars-30-in-first-five-months-of-2018-on-unprecedented-tightness

NEa. (n.d.). NEa - Home. Retrieved September 25, 2019 from https://www.emissieautoriteit.nl

Neelis, M., Patel, M., Blok, K., Haije, W., & Bach, P. (2007). Approximation of theoretical energy-saving potentials for the petrochemical industry using energy balances for 68 key processes. *Energy*, 32, 1104-1123.

Omnexus. (n.d.-a). RAMAPET R180 – Technical Datasheet. Retrieved October 9, 2019 from https://omnexus.specialchem.com/product/t-indorama-ventures-public-company-ramapet-r180

Omnexus. (n.d.-b). RAMAPET R182 (C) - Technical Datasheet. Retrieved October 9, 2019 from https://omnexus.specialchem.com/product/t-indorama-ventures-public-company-ramapet-r182-c

Papaspyrides, C. D., & Vouyiouka, S. N. (2009). *Solid State Polymerization*. Wiley, ISBN: 978-0-470-08418-2.

PDC. (2012). Productie van tereftaalzuur met hoge zuiverheid in een microreactor. Retrieved October 17, 2019 from https://www.rvo.nl/sites/default/files/rvo_website_content/EOS/KTOT01036EINDOPEN.pdf

Pirobloc. (n.d.-a). Thermal Fluid Heaters. Retrieved February 17, 2020 from https://www.pirobloc.com/wp-content/uploads/2017/08/Pirobloc-Thermal-Oil-Heaters.pdf

Pirobloc. (n.d.-b). Electric Thermal Fluid Heaters. Retrieved February 21, 2020 from https://www.pirobloc.com/en/products/thermal-fluid-electric-heater

Plasteurope.com. (2017, March 20). PET Recycling - India recycles 90% of its PET waste / Plastic turned into apparel, bedding and more. Retrieved February 25, 2020 from https://www.plasteurope.com/news/PET_RECYCLING_t236441

PlasticsEurope. (2018). Plastics - the Facts 2018. Retrieved November 20, 2019 from https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf

Plastics Insight. (n.d.-a). Purified Terephthalic Acid (PTA) Production, Price, Market and its Properties. Retrieved August 13, 2019 from https://www.plasticsinsight.com/resin-intelligence/resin-prices/purified-terephthalic-acid-pta

Plastics Insight. (n.d.-b). Polyethylene Terephthalate (PET): Production, Price, Market and its Properties. Retrieved August 8, 2019 from https://www.plasticsinsight.com/resin-intelligence/resin-prices/polyethylene-terephthalate

PlasticsToday (2012, April 19). Chinaplas: Titanium-based additive reduces PET reheat blow energy by 38%. Retrieved February 26, 2020 from https://www.plasticstoday.com/content/chinaplas-titanium-based-additive-reduces-pet-reheat-blow-energy-38/96391327617345

PolyOne. (n.d.). ColorMatrix^{TM} Joule^{TM} reheat additive for PET. Retrieved October 9, 2019 from https://www.polyone.com/products/polymer-additives/reheat-additives-pet/colormatrix-joule-pet

Polyestertime. (2018, November 30). Indorama Ventures announced force majeure at the PET factory in Rotterdam. Retrieved October 24, 2019 from https://www.polyestertime.com/indorama-ventures-force-majeure-pet

Popovic, P. (2017, July 25). Thailand's Indorama completes expansion of Rotterdam PTA plant. Retrieved September 18, 2019 from https://www.icis.com/explore/resources/news/2017/07/25/10127311/thailand-s-indorama-completes-expansion-of-rotterdam-pta-plant

Port of Rotterdam. (2007). Facts and figures: On Rotterdam’s oil and chemistry industry. Retrieved February 19, 2020 from https://issuu.com/alexkey/docs/rotterdamport

Port of Rotterdam. (2010). Facts & figures: Rotterdam Energy Port and Petrochemical Cluster. Retrieved August 7, 2019 from https://www.portofrotterdam.com/sites/default/files/Facts-Figures-Rotterdam-Energy-Port-and-Petrochemical-Cluster-Eng.pdf

Port of Rotterdam. (2016). Facts & figures on the Rotterdam energy port and petrochemical cluster. Retrieved August 7, 2019 from https://www.portofrotterdam.com/sites/default/files/facts-figures-energy-port-and-petrochemical-cluster.pdf

Port of Rotterdam. (2019a). Energie-infrastructuur in het Rotterdamse havengebied. Retrieved October 3, 2019 from https://www.portofrotterdam.com/sites/default/files/energie_infrastructuur_transitie_in_het_rotterdamse_havengebied.pdf

Port of Rotterdam. (2019b, February 11). Invitation to companies to express interest in the Rotterdam CCUS project. *Port of Rotterdam*. Retrieved November 28, 2019 from https://www.portofrotterdam.com/en/news-and-press-releases/invitation-to-companies-to-express-interest-in-the-rotterdam-ccus-project

Provinciaal blad. (2019, April 26). Kennisgeving beschikking Indorama Ventures Europe B.V. 2289.

Rijksoverheid. (2020). Statiegeld op kleine plastic flesjes voor minder zwerfafval. Retrieved 6 April 2021 from https://www.rijksoverheid.nl/actueel/nieuws/2020/04/24/statiegeld-op-kleine-plastic-flesjes-voor-minder-zwerfafval.

Rotunno, P., Lanzini, A., and Leone, P. (2017). Energy and economic analysis of a water scrubbing based biogas upgrading process for biomethane injection into the gas grid or use as transportation fuel. *Renewable Energy* 102: 417-432.

RVO. (2015). Verzamelvergunning verleend aan Indorama Ventures Europe B.V. voor het verrichten van handelingen met radioactieve stoffen. Retrieved August 18, 2019 from https://www.rvo.nl/sites/default/files/2015/09/20141177-05.pdf

RVO. (2019). Nederlandse lijst van energiedragers en standaard CO2 emissiefactoren, versie januari 2019. Retrieved February 20, 2020 from https://www.rvo.nl/sites/default/files/2019/05/Nederlandse%20energiedragerlijst%20versie%20januari%202019.pdf

Santhana Gopala Krishnan, P., & Kulkarni, S. T. (2008). *Polyesters and Polyamides*. Deopura, B. L., Alagirusamy, R., Joshi, M., Gupta, B. (ed.), chapter 1, 13. Elsevier, ISBN: 9781845694609.

Scarlat, N., Dallemand, J. & Fahl F. (2018). Biogas: Developments and perspectives in Europe. *Renewable Energy*, 129, 457-472. doi: 10.1016/j.renene.2018.03.006

SGC. (2012). Basic data on biogas. Retrieved December 20, 2019 from http://www.sgc.se/ckfinder/userfiles/files/BasicDataonBiogas2012.pdf

SGC. (2013). Biogas upgrading – Review of commercial technologies. Retrieved January 7, 2020, from http://www.sgc.se/ckfinder/userfiles/files/SGC270.pdf

Sinclair, N. (1998, June 4). Eastman inaugurates Rotterdam PET, PTA plants. *ICIS News*. Retrieved September 18, 2019 from https://www.icis.com/explore/resources/news/1998/06/04/60115/eastman-inaugurates-rotterdam-pet-pta-plants

Skindzier, M., Kaplan, K. & Roberts. A. (n.d.). Crystallizers. *Visual Encyclopedia of Chemical Engineering*. Retrieved February 14, 2020 from http://encyclopedia.che.engin.umich.edu/Pages/SeparationsChemical/Crystallizers/Crystallizers.html

Snijder, L., & Nusselder, S. (2019). Plasticgebruik en verwerking van plastic afval in Nederland. *CE Delft*.

S&P Global. (2019, January 9). Indorama's Rotterdam polyethylene terephthalate plant back in operation, force majeure still in place. Retrieved October 24, 2019 from https://www.spglobal.com/platts/en/market-insights/latest-news/petrochemicals/010919-indoramas-rotterdam-polyethylene-terephthalate-plant-back-in-operation-force-majeure-still-in-place

Staatscourant. (2013, August 28). Aanvraag vergunning Indorama Holdings Rotterdam B.V., DCMR Milieudienst Rijnmond. Retrieved August 13, 2019 from https://zoek.officielebekendmakingen.nl/stcrt-2013-24300.odt

Statiegeldalliantie (2019, January 15). Statiegeld als oplossing. Retrieved February 25, 2020 from https://statiegeldalliantie.org/2019/01/statiegeld-zo-werkt-het

Stichting Ons Statiegeld. (n.d.). Milieu-impact: Percentage recycling. Retrieved January 13, 2020 from http://www.echteheld.nl/milieu-impact/329/percentage_recycling

Taylor, G. (2001, August 7). Eastman picks Voridian as name for PET, fibres spin-off. *ICIS News*. Retrieved August 14, 2019 from https://www.icis.com/explore/resources/news/2001/08/07/144359/eastman-picks-voridian-as-name-for-pet-fibres-spin-off

Tecnon OrbiChem. (n.d.). The quest for cost-competitive bio-MEG sources continues. Retrieved January 14, 2020 from https://orbichem.wordpress.com/2017/06/02/the-quest-for-cost-competitive-bio-meg-sources-continues

Ter Telgte, P. (2012). Prospects of capture and geological storage of CO_2 from CHP plants in the Netherlands - A techno-economic analysis.

Thermona. (2010). Operation and Maintenance Manual for Electric Boilers. Retrieved November 25, 2019 from https://www.thermona.az/getattachment/Elektrokotle/Elektrokotle-standardni-rada/Kotel-THERM-EL-8/installation_user_manual_EL_5-8-9-14-15-23-30-38-45_AJ_2010-06.pdf.aspx

Thiele, Ulrich K. (2007). *Polyester Bottle Resins, Production, Processing, Properties and Recycling*. Heidelberg, Germany, pp. 85 ff, ISBN 978-3-9807497-4-9.

UL Prospector. (n.d.-a). RAMAPET® N180. Retrieved October 7, 2019 from https://materials.ulprospector.com/en/profile/pdf?E=229055

UL Prospector. (n.d.-b). RAMAPET® R180. Retrieved October 7, 2019 from https://materials.ulprospector.com/en/profile/pdf?E=229057

UL Prospector. (n.d.-c). RAMAPET® P184. Retrieved October 7, 2019 from https://materials.ulprospector.com/en/profile/pdf?E=229056

Van Berkel, A., & Hernandez, J. (2018). Taking the C out of steam.

Van Capellen, L., Croezen, H., & Rooijers, F. (2018). Feasibility study into blue hydrogen. *CE Delft*.

Van Dorp, R. (2013). Groen gas: een overzicht van innovatieve technieken en leveranciers. Retrieved November 22, 2019 from http://publications.tno.nl/publication/100031/9kEaoA/groengas2013.pdf

VNP. (2018). Decarbonising the steam supply of the Dutch paper and board industry.

Weil-McLain. (2016, January 8). Understanding Residential Boiler Efficiency Ratings. Retrieved January 8, 2020 from https://www.weil-mclain.com/news/understanding-residential-boiler-efficiency-ratings

Wellman International. (n.d.). High-Grade rPET Flake, from source. Retrieved October 3, 2019 from https://www.wellman-intl.com/rpet-flake

World Energy Council. (2019). New Hydrogen Economy - Hope Or Hype? Retrieved January 8, 2020 from https://www.worldenergy.org/assets/downloads/WEInsights-Brief-New-Hydrogen-economy-Hype-or-Hope-ExecSum.pdf

Zein, R., Konswa, A., Ibrahim, M., El-mittiny, E., Abdullah, H., Saeed, M., Saber, M., Mohsen, M., Fathy, M., Ismail, R., Metwally, R., & Esam, R. (2010). PET Production. Cairo University. doi: 10.13140/RG.2.1.3303.8163