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# DECARBONISATION OPTIONS FOR THE DUTCH ACTIVATED CARBON INDUSTRY

**Y. Abdallas Chikri and W. Wetzels**

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Manufacturing Industry Decarbonisation Data Exchange Network

PBL

## Colophon

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### Author(s)

Y. Abdallas Chikri and W. Wetzels

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### 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: [D. van Dam \(PBL\)](#), or [S. Gamboa \(TNO\)](#).

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This report has not been reviewed by Cabot Norit Nederland B.V. PBL and TNO are responsible for the content of the report. The decarbonisation options and parameters are explicitly not verified by the company.

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# Summary

Activated carbon is a material made of elemental carbon and it is characterized by its highly porous structure which has voids between the layers or sheets of carbon. Activated carbon is used to eliminate contaminants from fluids (liquids and gases) by trapping the contaminants in the pores through an adsorption process. Activated carbon is mainly manufactured in the form of powder and granulate.

Activated carbon is applied in many sectors, such as the fertilizer, pharmaceutical, cosmetics, petroleum and automobile industries. The material is used for solvent recovery, catalyst elimination and colour elimination in wastewater from industries. Other important applications are purification of water, air, beverages, food, pharmaceuticals and other fluids.

This report describes the activated carbon production in the Cabot Norit Nederland B.V. plant situated in Klazienaveen. The production capacity of the Klazienaveen plant is approximately 15 kilotonne/year. In 2020, the greenhouse gas emissions of the plant were 61,450 tonne CO<sub>2</sub>-eq. Cabot Norit Nederland B.V. also produces activated carbon in Zaandam, but the Zaandam plant does not participate in the EU Emissions Trading System and its production capacity is small in comparison with that of the Klazienaveen plant.

Activated carbon can be produced through a thermal treatment, the so-called physical activation. This process has two steps: carbonization and activation. The production process starts with the carbonisation of the raw material to obtain a char. Subsequently the char is activated in a gasification process at high temperature. In the Cabot Norit plant most of the carbon is activated through a steam activation process. The greenhouse gas emissions in the plant result from the combustion of waste gas released from the rotary kilns. The process in the kilns is self-sustaining and therefore the kilns are not fired. The energy consumption in the process is presented in Table 1.1. The emission intensity from the waste gas combustion is 5.6 tonne CO<sub>2</sub>/tonne activated carbon.

**Table 1.1**  
Main characteristics of activated carbon production in the Cabot Norit plant in Klazienaveen in 2020.

Parameter	Value	Unit	Source
Production capacity	15	kilotonne activated carbon/year	Estimation
Production volume 2020	11	kilotonne activated carbon/year	Estimation
Greenhouse gas emissions 2020	61.45	kilotonne CO <sub>2</sub> -eq	(NEa, 2021)
Emission factor	5.6	tonne CO <sub>2</sub> -eq/tonne activated carbon	Calculated from the greenhouse gas emissions and the estimated production volume

Spent activated carbon with accumulated contaminants inside can be regenerated. The regeneration of activated carbon can reduce the energy and feedstock consumption. In the Cabot Zaandam plant, spent activated carbon is regenerated through a thermal activation process. The main decarbonisation options analysed for the activated carbon manufacturing process are the substitution of raw materials by biomass-based raw materials, energy efficiency improvements and carbon capture technology. Alternative products, both conventional and non-conventional adsorbents, can substitute activated carbon.

# 1 Introduction

This report describes the current situation for the production of activated carbon in the Netherlands and the options and preconditions for its decarbonisation. The study is part of the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network). MIDDEN aims to support industry, policy makers, analysts and the energy sector in their common efforts to achieve deep decarbonisation. The MIDDEN project will update and elaborate further on options in the future, in close connection with the industry.

## 1.1 Scope

This report describes the activated carbon production in the Cabot Norit Nederland B.V. plant situated in Klazienaveen. The production process in the Cabot Norit plant is based on physical activation with steam. The plant regenerates spent activated carbon through a thermal activation process. The main decarbonisation options analysed for the activated carbon manufacturing process are the substitution of raw materials by biomass-based raw materials, energy efficiency improvements and carbon capture technology.

## 1.2 Reading guide

Chapter 2 introduces the activated carbon industry in the Netherlands. Chapter 3 describes the production processes for activated carbon. Chapter 4 describes the products and their application, while options for decarbonisation are systematically quantified and evaluated in Chapter 5. The feasibility of the decarbonisation options is discussed in Chapter 6.

## 2 Activated carbon production in the Netherlands

This chapter introduces the activated carbon industry in the Netherlands. It provides information on the Cabot Norit plant in Klazienaveen, the surroundings of the plant, the Cabot Corporation and the greenhouse gas emissions of the plant.

### 2.1 Activated carbon production in the Netherlands

Cabot Norit Nederland B.V. produces activated carbon in Zaandam and Klazienaveen. The production of activated carbon in the Netherlands started in 1916 in Zaandam with two kilns (Cabot Corporation, 2021). In Klazienaveen the production of activated carbon started in 1921 in the Purit factory. The Purit factory used peat, which was extracted from the peatlands in Drenthe, as raw material. Extraction of peat in the Netherlands virtually ceased in 1992 (Karel, Gerding, & De Vries, 2015), but peat is currently still the most important raw material used in the Klazienaveen plant.

**Figure 2.1**

Annual production of activated carbon in the Purit factory from 1924 to 1995 (Karel, Gerding, & De Vries, 2015).

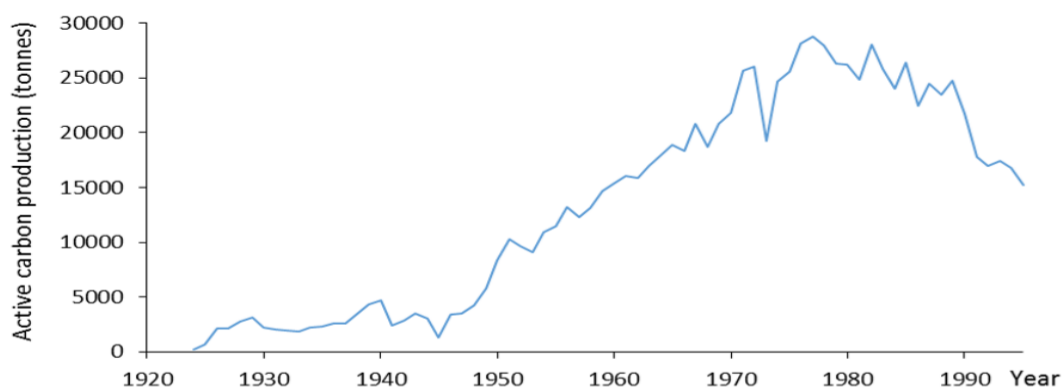


Figure 2.1 shows the annual production of active carbon by the Purit factory in 1924-1995 (Karel, Gerding, & De Vries, 2015). The plant became part of the Cabot Corporation in 2012 (Karel, Gerding, & De Vries, 2015). A production cluster was closed in 2019 which reduced the capacity of the plant to approximately 15 ktonne/year. The actual production in 2020 was approximately 11 ktonne (van Tholen, 2020)<sup>1</sup>.

The production capacity in the Zaandam plant is small in comparison with that of the Klazienaveen plant. Moreover, the plant in Zaandam has lower greenhouse gas emissions and does not participate in the EU Emissions Trading System. Therefore, this report only focuses on the production process and decarbonisation options for the Klazienaveen plant.

The Klazienaveen plant used to operate six rotary kilns, a chemical wash plant and a pharmaceutical plant. Currently, only three kilns are active due to a reorganization of the company in 2019. A 3 MW steam turbine is installed which can supply electricity to the grid. However, the steam turbine is currently not in use. The plant in Klazienaveen had approximately 160 employees in 2018. However, in December 2018 it was announced that there would be a reduction of 40 employees. Cabot Zaandam and Cabot Amersfoort (sales office and R&D) were also affected (RTV Drenthe, 2018).

The energy intensive companies in the north of the Netherlands are concentrated in two regions: Delfzijl-Eemshaven and Emmen. The Cabot Norit plant is located in Klazienaveen in the municipality of Emmen<sup>2</sup>. The GETEC PARK.EMMEN (formerly known as the EMMTEC Industry and Business Park) is situated approximately 10 km from Klazienaveen. The activities at the business park focus on fibres, composites and plastics made from virgin or recycled sources (ESCPP, 2021). Scattered over Drenthe there are also large dairy plants, process industry and in Wijster there is a municipal waste incineration plant (Werkbureau RES-regio Drenthe, 2021). Greenhouse horticulture is clustered in the Erica and Klazienaveen locations in Emmen (Provincie Drenthe, 2018).

The Cabot Norit Klazienaveen plant is part of the Cabot Corporation. The Cabot Corporation network consists of 42 manufacturing facilities in 20 countries. These facilities are organized in three business segments: performance chemicals, reinforcement chemicals and purification solutions. The Klazienaveen, Zaandam and Amersfoort facilities are part of the purification solutions segment. The operating revenues of Cabot Corporation were \$3,337 million in 2019 (Cabot Corporation, 2020). The net turnover in 2015-2016 of Cabot Norit Nederland B.V., which includes the Klazienaveen, Amersfoort and Zaandam sites, was €196.9 million (DBO Audit & Assurance B.V., 2017).

In 2020, the greenhouse gas emissions of the Cabot Norit Activated Carbon plant in Klazienaveen were 61,450 tonne CO<sub>2</sub>-eq (see Table 2.1). In 2018, the emissions were 120,267 tonne CO<sub>2</sub>-eq. The decrease of emissions has to do with the reorganization that took place in 2019.

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<sup>1</sup> In this personal communication, also other information about the production processes, products and raw materials of the Klazienaveen and Zaandam plants was shared that has been used for this report.

<sup>2</sup> Address: Mr. Ovingkanaal Oostzijde 3, 7891 EV, Klazienaveen.

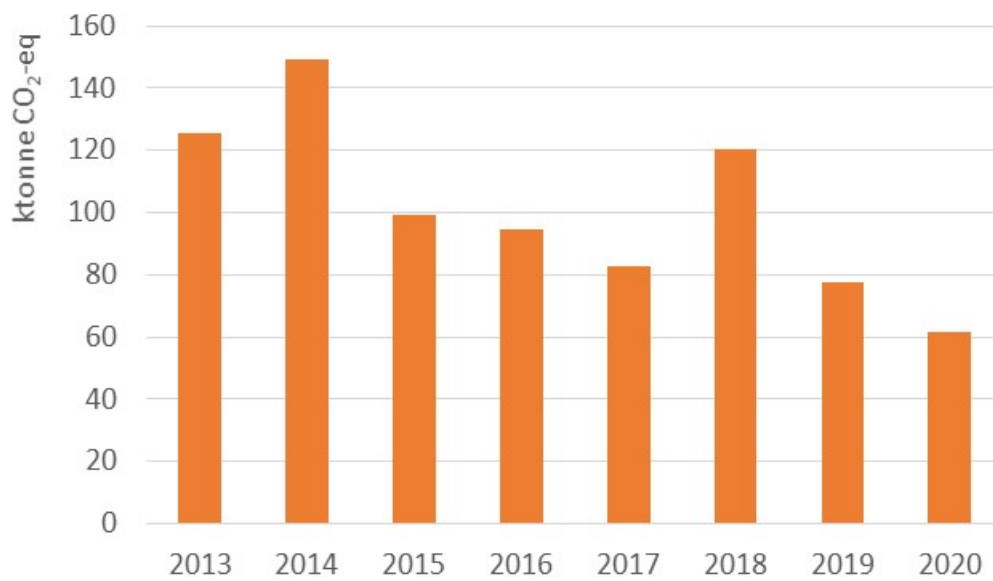
**Table 2.1**

Greenhouse gas emissions in the Cabot Norit Activated Carbon plant in Klazienaveen from 2013 to 2020<sup>3</sup> (NEa, 2021).

Year	Greenhouse gas emissions (tonne CO <sub>2</sub> -eq)
2013	125,468
2014	149,477
2015	99,394
2016	94,831
2017	82,764
2018	120,267
2019	77,639
2020	61,450

**Figure 2.2**

Greenhouse gas emissions in the Cabot Norit Activated Carbon plant in Klazienaveen from 2013 to 2020 (NEa, 2021).



<sup>3</sup> Permit number: NL-200500006.



# 3 Activated carbon processes

This chapter describes the production processes for activated carbon. First, an overview of the process is presented. Next, the mass balance and energy balance for the Cabot Norit Activated Carbon plant in Klazienaveen are estimated.

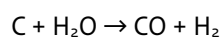
## 3.1 General process description

Activated carbon consists of carbon atoms in an aromatic configuration which are randomly linked. The difference with other carbon forms is that the structure is based on groups of atoms set in a disordered manner. The arbitrary bonding provides a porous structure which has voids between the layers or sheets of carbon. This makes it very suitable for adsorption of impurities in fluids and gases (Koehlert, 2017).

Applications of activated carbon depend on the pore size and the pore volume specifications. These parameters are controlled in the production process by the selected raw material, activation process conditions and the post-processing phases. There are three forms of activated carbon: powder, granulate or extrudate. Each of these forms can be provided in different particle sizes (Koehlert, 2017).

The activated carbon production process is performed through the following steps:

- 1) *Drying*: Elimination of the moisture contained in the raw material.
- 2) *Devolatilization*: Volatile organic compounds (VOCs) are formed in a cracking reaction of the raw material. This step takes place at 100-400 °C.
- 3) *Charring*: Charring occurs at temperatures between 400-600 °C. A carbonaceous char residue with high molecular weight is formed from the organic material. Porosity and internal surface area are starting to take shape.
- 4) *Activation*: The activation process occurs at temperatures between 700 and 1,050 °C in a steam atmosphere. The process temperature depends on the specification of the pores. Part of the carbon is gasified as presented in the chemical reaction below. Approximately half of the carbon is gasified in order to create the pore volume (Koehlert, 2017).



## 3.2 Raw materials

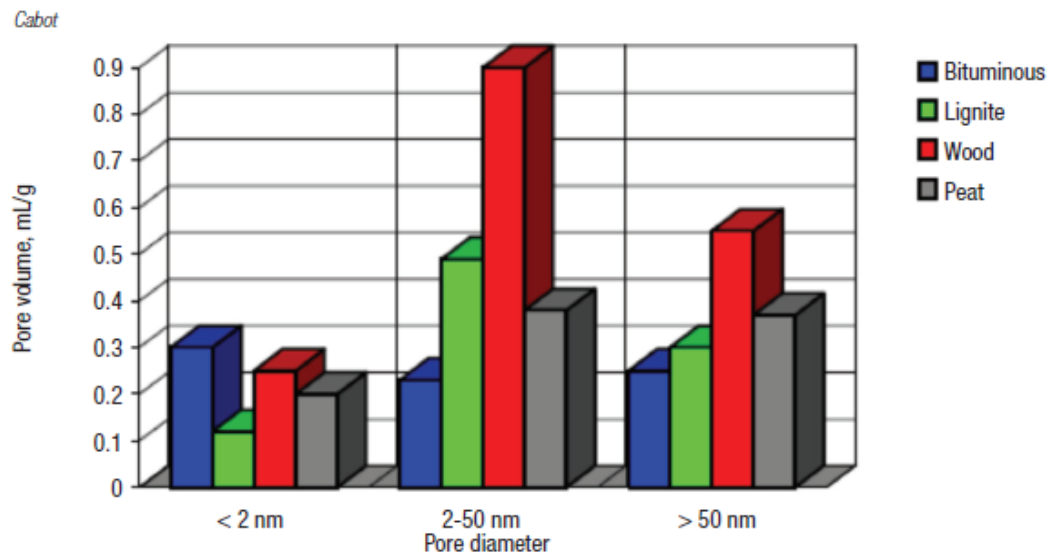
The required properties of the final product and economics determine which raw material is used for the process. The raw material has a considerable influence on the specifications (pore size, volume, purity, hardness, adsorptive capacity) (Tadda, et al., 2016).

Activated carbon can be made from a large variety of raw materials. The raw materials used for activated carbon manufacturing are carbonaceous materials such as coal, lignite, wood and peat (Cabot Corporation, 2018). Agricultural waste materials such as coconut shells, olive stones, sawdust, walnut shells can be used as well. Non-renewable raw materials (lignite, peat, coal) often have a higher carbon content than agricultural waste materials. However, the second type of raw materials is more sustainable.

Commonly used raw materials are coal, coconut shell and wood. Less conventional raw materials include peat, olive stones and scrap tires (Yahya, Al-Qodah, & Nhag, 2015).

**Figure 3.1**

Properties of activated carbon depending on the raw material (Koehlert, 2017)



The raw materials are pre-treated before being fed into the main process. Pre-processing is important for controlling the properties of the activated carbon. The materials can be crushed, milled, briquetted, mixed with binders and extruded.

In 2001, peat was the main raw material in the Klazienaveen plant. Charcoal, lignite and charred coconut shells were also used (Gjaltema, 2001). Currently, the most important raw material is peat, followed by lignite and coconut shells. The Klazienaveen plant produces approximately 70 types of activated carbon in the form of powder or granules. The pharmaceutical products are often based on coconut shells or peat while products for the food industry are typically made from peat. Gas and water purification products are bulk products usually made from lignite.

Coconut shells need to be crushed before entering the drying process. In the Klazienaveen plant the crushing process does not take place, as the raw materials are already crushed.

### 3.3 Activation methods: physical and chemical activation

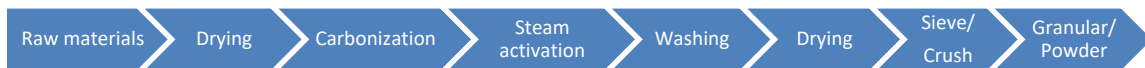
The transformation of the raw materials into activated carbon can be achieved through two processes: physical activation or chemical activation. In this section the physical activation process is described in detail as this process is used in the Klazienaveen plant. Chemical activation is also discussed briefly.

### 3.3.1 Physical activation

Activated carbon can be produced through a thermal treatment, the so-called physical activation. This process has two steps: carbonization and activation. First, the dried raw material is carbonized to obtain char. Subsequently, the char is activated through gasification at high temperature. In the Cabot Norit plant in Klazienaveen most of the carbon is activated through a steam activation process.

**Figure 3.2**

Diagram of the physical activation production process (Kuraray, 2019).



#### **Step 1: Carbonization (devolatilization, carbonization and postcarbonization)**

Carbonization is a thermo-chemical treatment which takes place in the absence of oxygen, traditionally in kilns. The thermo-chemical reaction is called pyrolysis and results in three products: char, tar and gas. The pyrolysis can be performed at different speeds depending on the desired final product. Slow pyrolysis aims to produce a solid product (char) while fast pyrolysis results in a liquid product (tar) (Hagemann, et al., 2018).

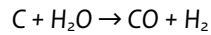
Carbonization starts at a temperature of 200 °C with the devolatilization process during which tar is formed. The decomposition of the materials that are combustible releases heat. The main phase of the carbonization occurs at temperatures between 450 °C and 520 °C. In this phase methane, hydrogen and carbon monoxide are formed. The fixed carbon content increases significantly. Afterwards, the post-carbonization phase takes place between 520 °C and 1000 °C (Grumpelt & Deilmann, 2005).

This process can be performed in a fluidized bed and in rotary kilns. In the Klazienaveen plant the process takes place in rotary kilns. In continuous processes the different phases of carbonization overlap. At high temperatures, the tar is decomposed into hydrogen, methane and hydrocarbons. The process is performed using indirect heat in an oxygen-free atmosphere. Under these conditions the energy content of the gas rises (Grumpelt & Deilmann, 2005).

In the Klazienaveen plant, the gases produced in the pyrolysis can be used for power generation. The gases are combusted in a waste gas boiler to generate steam. The high-pressure steam can be used for electricity generation while the low-pressure steam is used for the drying process (Gjaltema, 2001). In 2010, about half of the electricity that was generated was used in the plant and the other half was sold to the grid (van Baal, 2010). There still is a 3 MW steam turbine that can supply electricity to the grid, but this steam turbine is currently not in use.

## Step 2: Activation

The activation phase takes place at temperatures between 700 °C and 1050 °C in a steam atmosphere. The temperature of the activation process depends on the desired pore structure (Koehlert, 2017). The char is introduced in the rotary kiln in which the temperature is raised to approximately 900 °C. Then steam is injected to eliminate the reactive carbon, thereby generating porosity (Yahya, Al-Qodah, & Nhag, 2015). The activation process goes through three stages: 1) opening inaccessible pores, 2) creating new pores, 3) expansion of the existing pores (Maneerung, et al., 2015). The steam reacts with the carbon forming carbon monoxide and hydrogen.

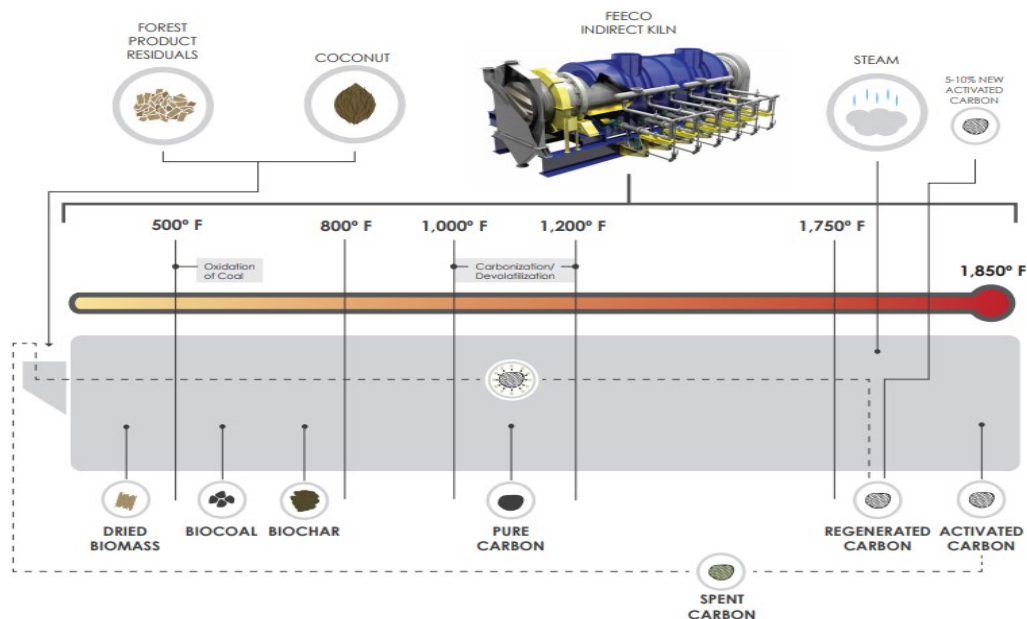


The steam activation process is the most common and it is performed at high temperature in rotary kilns, shaft kilns, multi-hearth furnaces or fluidized beds. In the Klazienaveen plant rotary kilns are used. The process in the kilns is self-sustaining and therefore the kilns are not fired. Gas lances are used when the kilns are cold.

The rotary kiln in which the raw materials are converted into activated carbon can be forty meters long and have a diameter of five meters (van Baal, 2010). During this process, the atmosphere contains hydrocarbons in the absence of oxygen (Henning & von Kienle, 2010).

**Figure 3.3**

Activated carbon production in a rotary kiln (FEECO International, 2019).



### 3.3.2 Chemical activation

Chemical activation produces activated carbon in a different way than physical activation. During this process the raw material is mixed with a dehydrating agent and then heated at temperatures between 400 °C and 700 °C (Koehlert, 2017). Dehydrating agents or oxidizing agents that are commonly used are  $ZnCl_2$ ,  $H_3PO_4$  and  $KOH$ . These agents influence the pyrolysis decomposition and could prevent the formation of tar and ash, influencing the carbon yield (Yahya, Al-Qodah, & Nhag,

2015). The chemical activation process does not take place in the Klazienaveen plant and is therefore not analysed in detail. However, this process is carried out in the Zaandam plant.

**Figure 3.4**

Diagram of the chemical activation production process (Kuraray, 2019).



## 3.4 Post-processing

The activated carbon exiting the activation unit is further processed in the following steps (Koehlert, 2017):

- 1) *Washing*: Soluble impurities and ash are removed with an acid wash. High purity levels are required for applications such as capacitors, pharmaceuticals and food. In the Klazienaveen plant acid-washed steam-activated carbons are manufactured.
- 2) *Sizing*: This process transforms the final product into granules, extruded forms or powder in rollers, hammers or mills. In the Klazienaveen plant most of the products are powder or granular activated carbon.
- 3) *Shaping*: The surface-to-volume ratio and pressure drop in powdered activated carbon can be optimized by shaping it into cylinders, tubes, honeycombs or extruded forms. Extrusion processes no longer take place in the Klazienaveen plant, but are used in Zaandam.
- 4) *Impregnation*: Chemicals are added to the structure so that more elements can be adsorbed on activated carbon. This added functionality makes the activated carbon suitable for more applications. Silver, metal salts and amines are examples of chemicals used for impregnation. Potassium iodide and sodium hydroxide can be used for sulphur elimination. Impregnation does not take place in the Klazienaveen and Zaandam plants.
- 5) *Re-activation (regeneration)*: Recycling of the activated carbon can be performed through a re-activation process. The activated carbon that is filled with contaminants is thermally treated in order to eliminate the volatile contaminants and to restore the adsorption capacity of the pores. In this process, 5 to 15 percent of the material is lost and has to be replaced by virgin material. The regeneration process does not occur in the Klazienaveen plant, but does take place in Zaandam.

## 3.5 Mass balance and energy balance

In this section the mass balance and energy balance as well as the greenhouse gas emissions are presented. The process in the kilns is almost self-sustaining. Therefore, the only energy input considered to the kilns are the raw materials. A boiler is used to provide steam to the activation process. The hot gases released, which are rich in CO and H<sub>2</sub>, are used in a heat exchanger and a waste boiler to recover the heat into the process.

### **Raw materials**

Peat is the main raw material used in the Klazienaveen plant, but lignite and coconut shells are also used. The composition of the different raw materials is presented in Tables 3.1 and 3.2. To obtain

estimates for the mass balance and energy balance, it is assumed that only peat is used as a raw material.

**Table 3.1**  
Raw materials composition, proximate analysis (% w/w)

Raw Material	Mois-ture	Ash	Vola-tiles	Reference
Peat	46.3	2.5	36.2	(ECN, 2006)
Coconut shells	8.2	0.1	73.1	(Yahya, Al-Qodah, & Nhag, 2015)
Lignite	48	14	23.4	(ECN, 2006)

**Table 3.2**  
Raw materials composition, ultimate analysis (% w/w).

Raw Material	C	H	N	S	O	Reference
Peat	52.9	5.4	1.7	0.2	39.8	(ECN, 2006)
Coconut shells	48.6	6.5	0.1	0.1	44.6	(Yahya, Al-Qodah, & Nhag, 2015)
Lignite	41	2.4	1.1	0.9	31	(ECN, 2006)

### Drying

The raw material is dried before entering the carbonization phase. Peat has a relatively high moisture content. In Klazienaveen the peat is dried in a storage unit using air currents. The energy consumption in the drying process is relatively small and not considered in this report.

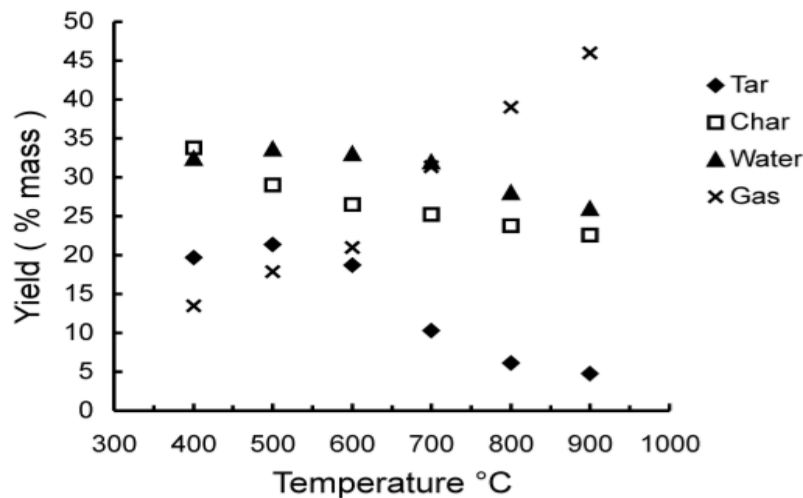
### Carbonization

In the carbonization process the dried raw material is introduced in a kiln to be carbonized. The carbonization process is usually performed between 400 °C and 850 °C. The goal of this process is to eliminate the volatile matter and obtain a char with a high content of fixed carbon (Yahya, Al-Qodah, & Nhag, 2015).

During the pyrolysis processes three products start to form: char, tar and gas. At increasing temperatures, the yield of the char decreases while the gas yield increases (Sutcu, 2007). The temperature of the carbonization process can affect the yield of activated carbon. At higher carbonization temperatures the activation burn-off is higher and consequently the yield of activated carbon drops (Yahya, Al-Qodah, & Nhag, 2015). Figure 3.5 shows the yield of the products from coconut shells pyrolysis at different temperatures. The raw material is decomposed into char, tar, gas and water.

In the Klazienaveen plant the carbonization and the steam activation occur in the same kiln, which reaches temperatures between 850 °C and 900 °C (Henning & von Kienle, 2010). This is a continuous process and takes place in slowly rotating ovens (rotary kilns) (Ministerie van Volksgezondheid, 2016). This process is self-sustained due to the release of energy during the carbonization. The main source of energy is the raw material introduced in the kiln.

**Figure 3.5**  
Coconut shells pyrolysis yields for different temperatures (Fagbemi, Khezami, & Capart, 2001)

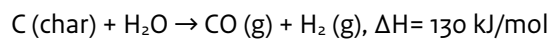


### Activation

The char obtained in the carbonization process is activated through physical activation. The char is gasified at high temperatures with steam, CO<sub>2</sub> or a mixture of gases to eliminate the reactive carbon, which increases the porosity (Yahya, Al-Qodah, & Nhag, 2015).

The pore size, the surface area and the amount of burn-off of the char depend on the temperature and the activating agent. The burn-off degree with CO<sub>2</sub> is higher than with steam activation. Moreover, the activation with CO<sub>2</sub> is faster than with steam.

For this estimate, it is assumed that the char is gasified with steam at 900°C (Arena, Lee, & Clift, 2016). Accordingly, the yield of the process is approximately 57.5%. This means that 42.5% of the char is gasified (Arena, Lee, & Clift, 2016). The activated carbon is classified by the surface area, the pore volume and the pore size. At increasing temperatures, the surface area increases (Maneerung, et al., 2015). Based on a 57.5% yield, the amount of char needed to produce 1 tonne of activated carbon is approximately 1.74 tonnes of char.



The steam required for the activation process is produced in a heat exchanger using the hot gases released at the end of the kiln. The steam produced is superheated steam at 900 °C and 1 bar (Gu, Bergman, Anderson, & Alanya-Rosenbaum, 2017) (Hernandez, Aquino, & Capareda, 2007). The amount of steam required for the activation process is 1.5 tonnes/tonne activated carbon (Arena, Lee, & Clift, 2016).

In the mass balance it is assumed that the gases formed in the pyrolysis process and the activation process are released together at the end of the process as a hot gas. Waste heat is recovered from the hot gas through a heat exchanger. Subsequently a condenser is used to separate the water from the non-condensable gases in the hot gas. The non-condensable gases are used as fuel in a waste gas boiler. These gases are rich in hydrogen and carbon monoxide.

We assume that the heat recovered from the hot gas in the heat exchanger and the waste gas boiler is used for the process in the kiln.

### Sizing

Finally, the activated carbon produced is sized (by crusher and tumbling machines), washed and dried (Ministerie van Volksgezondheid, 2016). In the Klazienaveen plant the washing process is sometimes used to increase the purity of the product, typically for applications in the pharmaceutical industry. For the mass balance, washing and sizing are not considered.

### Mass balance, energy balance and greenhouse gas emissions

Here, the mass balance, energy balance and greenhouse gas emissions of the processes at the Cabot Norit plant in Klazienaveen are estimated based on the characteristics in Table 3.

First, the carbon content of the raw material and the products is used to calculate the quantity of dried peat required to produce 1 tonne of activated carbon. Secondly, the emission intensity of the process is calculated assuming a production volume of 11 kilotonne activated carbon year and greenhouse gas emission of 62 kilotonne CO<sub>2</sub>-eq. The emissions are released in one stream after the afterburner in which the non-condensable gases rich in hydrogen and carbon monoxide are combusted. Finally, the mass of dry peat required is based on the peat composition presented in Table 3.3.

**Table 3.3**

Main characteristics of activated carbon production in the Cabot Norit plant in Klazienaveen in 2020.

Parameter	Value	Unit	Source
Production capacity	15	kilotonne activated carbon/year	Estimation
Production volume 2020	11	kilotonne activated carbon/year	Estimation
Load factor 2020	0.73	-	Calculated from the production capacity and the estimated production volume
Greenhouse gas emissions 2020	61.45	kilotonne CO <sub>2</sub> -eq	(NEa, 2021)
Emission factor	5.6	tonne CO <sub>2</sub> -eq/tonne activated carbon	Calculated from the greenhouse gas emissions and the estimated production volume

A mass balance for production of activated carbon from coconut shells (Arena, Lee , & Clift, 2016) is used as a reference and is adapted to the process in the Klazienaveen plant. Table 3.5 presents the mass balance. The main source of emissions in the Klazienaveen plant is the combustion of the non-condensable gases in the waste gas boiler.



**Table 3.4**

Estimated carbon balance of activated carbon production in the Cabot Norit plant in Klazienaveen in 2020.

Commodity	Input/output	Mass (tonne)	Source	Carbon Content (tonne)	Source
Dry peat	Input	4.6	Estimation based on the carbon content of dry peat, the amount of carbon in the product and the CO <sub>2</sub> emission.	2.4	Estimation based on the amount of carbon in the product and the CO <sub>2</sub> emission.
Activated carbon	Output	1	-	0.91	(Arena, Lee, & Clift, 2016)
CO <sub>2</sub> emission	Output	5.6	Calculated from the greenhouse gas emissions and the estimated production volume	1.5	Calculated using the emission factor, the atomic weight of carbon (12) and of oxygen (16).

The process in Klazienaveen is self-sustained due to the release of energy during the carbonization. The main source of energy is the raw material, in this case peat. The energy balance is calculated considering a calorific value of 9.76 MJ/kg for peat (RVO, 2020). The calorific value of activated carbon is approximated to the calorific value of 30.0 MJ/kg of charcoal (RVO, 2020).

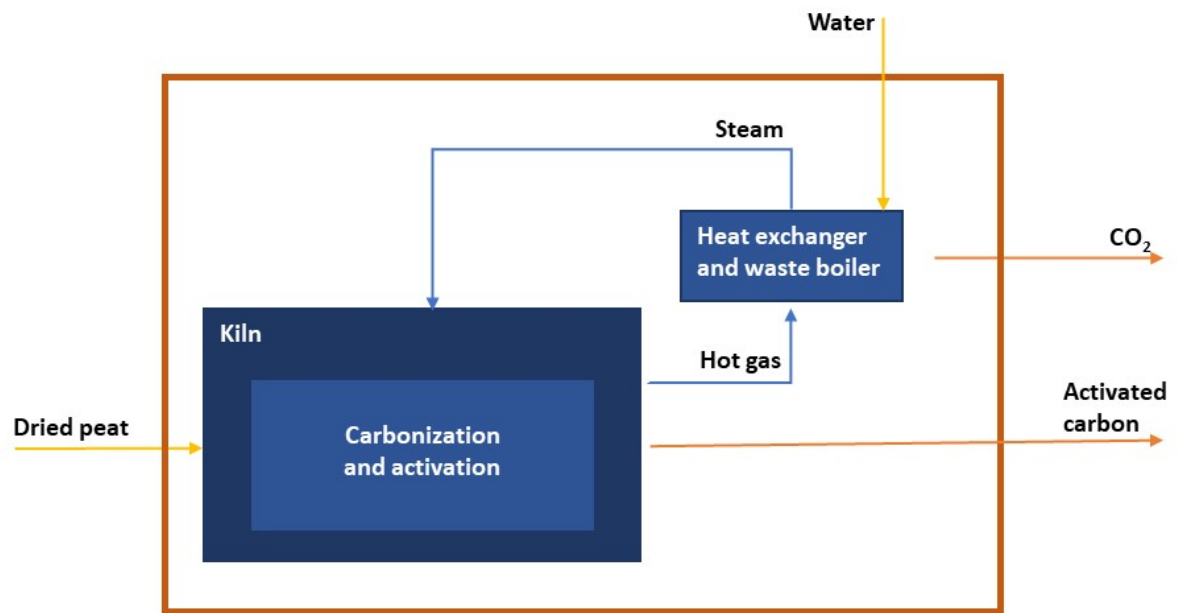
**Table 3.5**

Energy balance of activated carbon production in the Cabot Norit plant in Klazienaveen in 2020.

Input	Energy (GJ/tonne activated carbon)	Output	Energy (GJ/tonne activated carbon)
Peat	84	Activated carbon	30
Peat		Energy loss	54

**Figure 3.6**

Diagram of the mass and energy balance of the activated carbon production process.



# 4 Activated carbon products, applications and regeneration

This chapter discusses the applications of activated carbon and presents an overview of the worldwide consumption and market. In addition, it describes regeneration of activated carbon.

## 4.1 Activated carbon applications

Activated carbon is mainly made of elemental carbon which has been treated with heat and steam. This material is characterized by a high porosity that is created during the carbonization and activation process. Activated carbon is used to eliminate contaminants from fluids (liquids and gases) by trapping the contaminants in the pores through an adsorption process. Activated carbon is mainly manufactured in the form of powder and granulate. The products can have different sizes and forms, and can be made from different raw materials (Cabot Corporation, 2018).

Worldwide, approximately 38% of the activated carbon is consumed for water treatment. Gas and air purification represent circa 24% of the activated carbon consumption, while food processing represents circa 19%. These percentages might differ by region depending on the applications (IHS Markit, 2020).

Activated carbon is applied in many sectors, such as the fertilizer, pharmaceutical, cosmetics, petroleum and automobile industries. The material is used for solvent recovery, catalyst elimination and colour elimination in wastewater from industries (Tadda, et al., 2016). Other important applications are purification of water, air, beverages, food, pharmaceuticals and other fluids.

## 4.2 Regeneration of spent activated carbon

Spent activated carbon with accumulated contaminants inside can be regenerated. A thermal process similar to steam activation is the most common method of regeneration. This process can be applied to extruded and granular activated carbon.

Regeneration of activated carbon can reduce the energy and feedstock consumption. There are numerous methods to reactivate the activated carbon. The technique used depends on the costs and type of contaminant accumulated in the activated carbon. The different methods are briefly described from literature (El Gamal, Mousa, El-Naas, Zacharia, & Judd, 2018):

- Steam regeneration of granular activated carbon from wastewater treatment is performed in five steps: thermal decomposition of activated carbon, oxidation with steam, vaporization of adsorbate, thermal decomposition and carbonization of the contaminants and finally the oxidation of the carbonized contaminants with steam.
- Thermal regeneration treatment applied to spent activated carbon eliminates the contaminants contained in the solid. Pores recover their original volume, which restores the adsorptive capacity. During this process between 5% and 15% of the activated carbon

is lost. Therefore, fresh material is added (Koehlert, 2017). This process includes drying, pyrolysis and gasification of the contaminants. This method is time consuming.

- The chemical regeneration process uses chemical reagents to decompose the adsorbates. The efficiency of this process depends on the reactivity of the adsorbents with the reagents. The efficiency of chemical regeneration of granular activated carbon is commonly lower than 70%.
- Microwave regeneration is based on heating of the solid, which goes through a thermally activated reaction. In this case the carbon should be a microwave absorber. This method requires less energy than conventional methods.
- Another method is wet oxidation regeneration. In this process the activated carbon is introduced in an aqueous solution and heated to 150-200°C. During this process the contaminants are decomposed.
- Electrochemical regeneration can be performed through different mechanisms. This technology is commercially available for organic contaminants from water.
- Bio-regeneration can be used when organic contaminants can be desorbed easily. This method uses microbial colonies which interact with the contaminants. The applicability of this process depends on factors such as the biodegradability of the contaminants and the physico-chemical characteristics of the activated carbon.

Bio-regeneration involves lower costs than steam and chemical regeneration (El Gamal, Mousa, El-Naas, Zacharia, & Judd, 2018). Microwave regeneration has been applied but its application is currently limited (Li, Jin, Su, Lu, & Li, 2018).

The regeneration of powder activated carbon through pyrolysis was analysed in a pyrolysis furnace in which the energy consumed to regenerate 1 tonne of waste powder activated carbon was 40 kWh. This energy consumption represents 25% of the energy required to produce 1 tonne of fresh powder activated carbon (160 kWh) (Li, Jin, Su, Lu, & Li, 2018).

In the Cabot Zaandam plant granular activated carbon is regenerated through thermal activation. According to Cabot, the CO<sub>2</sub> released in the reactivation process amounts to approximately 20% of the emissions released during manufacturing of virgin granular activated carbon. This process requires 10% of virgin activated carbon. The process is performed in kilns at temperatures of 850°C and above. Cabot ensures that 97% of the adsorptive capacity is restored (Cabot Corporation, 2021).

# 5 Options for decarbonisation

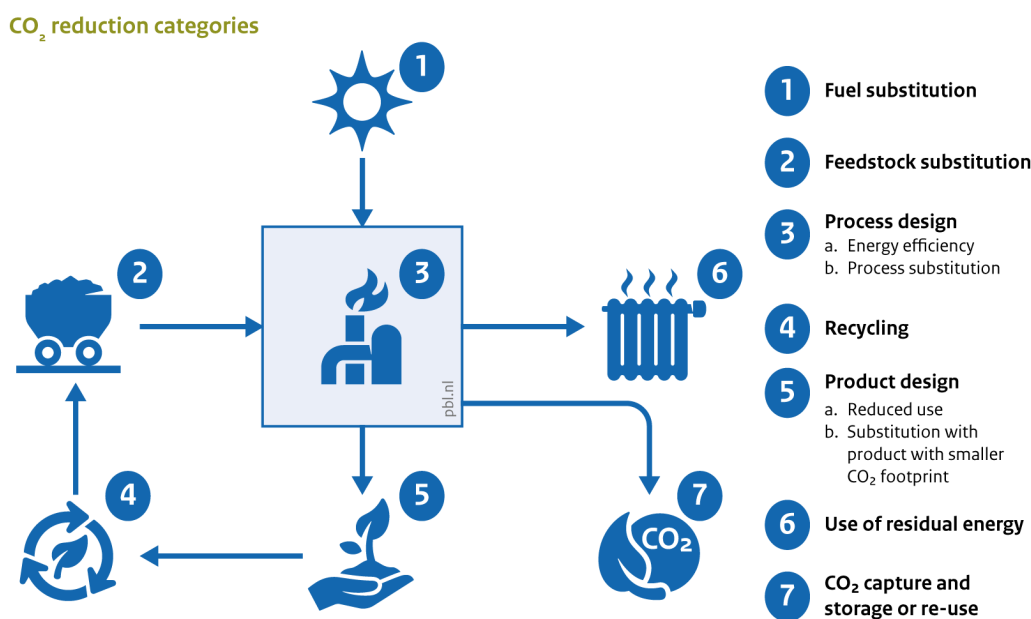
This chapter discusses options for decarbonisation of the activated carbon production process in Klazienaveen.

The main decarbonisation options that have been identified are:

- Substitution of raw materials,
- Energy efficiency improvements, and
- Carbon capture, utilization and storage.

Another option that is discussed is the substitution of activated carbon by other products. Regeneration of activated carbon can reduce energy and feedstock consumption, as was discussed in section 4.2.

**Figure 5.1**  
CO<sub>2</sub> reduction categories



Bron: PBL

## 5.1 Substitution of raw materials

The fossil greenhouse gas emissions in Klazienaveen are due to the use of peat and lignite. To reduce the fossil emissions, other raw materials could be used. Biomass can be used as a source of carbon. For instance, coconut shells are used to produce activated carbon for the pharmaceutical industry. Substitution of the raw materials may influence the quality and potential applications of the products.

The substitution of peat by coconut shells would lead to an emission intensity of approximately 4 tonnes of biobased CO<sub>2</sub>-eq per tonne of activated carbon (Arena, Lee , & Clift, 2016). In case of combining the use of biomass and carbon capture and storage (CCS), the emissions could become negative.

## 5.2 Energy efficiency improvements

The Cabot Corporation has reduced its direct and indirect emissions by increasing the efficiency of its production processes and investing in waste heat recovery (Cabot Corporation, 2021). The process in the Klazienaveen plant can be modernized to reduce energy losses in the long rotary kilns. Energy can also be saved by using peat with a lower moisture content, since the moisture in the peat causes energy losses in the rotary kilns. Electricity can be saved by using more efficient electromotors or by replacing the current lighting by LED lighting. The waste gas released in the kilns is rich in carbon monoxide and hydrogen. These gases could be used more efficiently if they were separated from the waste gas stream.

## 5.3 Carbon capture, utilization and storage

Carbon Capture, Utilisation and Storage (CCUS) is a solution to reduce greenhouse gas emissions from the flue gas. Post-combustion technology uses membranes, solvents and sorbents to capture the CO<sub>2</sub> in the stream. The most advanced technology for post-combustion capture is based on amine solvents. Here chemical absorption with monoethanolamine (MEA) solvents is considered. This technology has been applied on a commercial scale (IEA, 2016). In the Klazienaveen plant we consider one source of emissions, namely the combustion of non-condensable gases in the waste gas boiler.

The exhaust gas is first pressurized before entering the system. Then it is water washed and treated to remove to contaminants. Subsequently the clean gas is conveyed to the MEA solvent which purifies the gas. The rich solvent is then regenerated in the stripper with heat releasing the CO<sub>2</sub> at the top of the stripper.

**Figure 5.2**  
Post-combustion carbon capture adsorption process (Global CCS Institute, 2019).

### Post-combustion capture (absorption process)

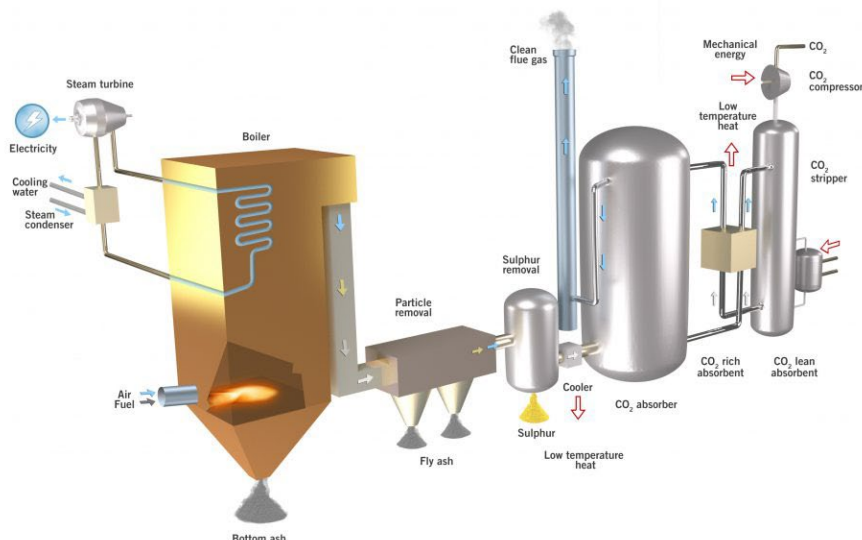


Table 5.1 provides techno-economic parameters for post-combustion capture of low concentration CO<sub>2</sub> streams (<20%vol) for liquefied transport (compressed to ~110 bar) with MEA solvents with a 90% capture rate. This technology is typically used in combination with CO<sub>2</sub> transport by truck or ship.

The capacity of the carbon capture unit that would be needed at the Klazienaveen site can be estimated to be 80 kilotonnes captured CO<sub>2</sub> per year. This is based on the maximum production capacity (15 kilotonnes of activated carbon), the emission factor (5.6 tonne CO<sub>2</sub>/tonne activated carbon) and the carbon capture ratio of the system (90%). The costs in Table 5.1 are based on a unit with a larger capacity.

**Table 5.1**  
Techno-economic parameters for post combustion CO<sub>2</sub> capture and compression for liquefied transport.

Parameter	Value	Unit	Comment
<b>CAPEX</b>	348 (273-419)	EUR <sub>2020</sub> /tonne CO <sub>2</sub> captured/year	CAPEX for capture, purification, compression, and liquefaction. Costs based on a unit with capacity of about 0.7 MtCO <sub>2</sub> captured/year. High range for retrofit to existing installation, mid range based on new installation (Lensink & Schoots, 2021). Low range costs are based on (Husebye, Brunsvold, Roussanaly, & Zhang, 2012), for 13.5%vol CO <sub>2</sub> concentration (deflated from 2012 to 2020 EUR based on European HICP index), combined with compression/network costs from (Lensink & Schoots, 2021). Transport and storage equipment is excluded.
<b>Fixed</b>	10.5 (8.2-12.6)	EUR <sub>2020</sub> /tonne	3% of CAPEX. Transport and storage

Parameter	Value	Unit	Comment
<b>operating and maintenance costs</b>		CO <sub>2</sub> captured/year	costs are excluded from this value. Based on (Lensink & Schoots, 2021)
<b>Technical lifetime</b>	20 (15-25)	year	(Lensink & Schoots, 2021) , (Husebye, Brunsvold, Roussanaly, & Zhang, 2012), (Berghout, Kuramochi, van den Broek, & Faaij, 2015),
<b>Electricity consumption</b>	0.76 (0.46-0.9)	GJ/tonne CO <sub>2</sub> captured	50 kWh/tCO <sub>2</sub> for capture, 162 kWh/tCO <sub>2</sub> for liquefaction based on (Lensink & Schoots, 2021). Upper limit based on (Berghout, Kuramochi, van den Broek, & Faaij, 2015), lower limit based on (Danish Energy Agency, 2021).
<b>Steam consumption</b>	3.7 (3-4)	GJ/tonne CO <sub>2</sub> captured	1028 kWh <sub>th</sub> /tCO <sub>2</sub> for post-combustion capture based on (Lensink & Schoots, 2021). Upper limit based on 3.5-4 GJ/t range from Berghout et al. (2015), lower limit based on Danish Energy Agency (2021).
<b>Capture rate</b>	90	%	CO <sub>2</sub> emissions remain after capture from the original flue gas stream. Based on (Lensink & Schoots, 2021).
<b>TRL</b>	9	-	MEA solvent capture and CO <sub>2</sub> compression techniques have been commercially applied (Global CCS Institute, 2021).

## 5.4 Substitution of activated carbon by other products

The main applications of activated carbon are water treatment and gas and air purification. For both applications, activated carbon can be substituted by other products. Crini et al. have studied conventional and non-conventional adsorbents for wastewater treatment (Crini, Lichtfouse, Wilson, & Morin-Crini, 2019). Conventional adsorbents used for the removal of pollutants from wastewater are commercially available activated carbon, inorganic materials (e.g. activated alumina, silica gel, zeolites and molecular sieves), and ion-exchange resins (e.g. polymeric organic resins). Activated carbon is the main commercially used adsorbent followed by zeolites. Activated carbon provides the best results to remove different types of contaminants. Non-conventional adsorbents are, e.g., activated carbons produced from agricultural solid waste, clays, red mud, biosorbents (chitosan) and alginates.

Alternatives to activated carbon on an industrial scale are zeolites, activated alumina, silica gels, ion-exchange resins and sand. Non-conventional 'green' adsorbents are not yet used on industrial scale. The non-conventional materials used are abundantly available in nature and inexpensive, but the adsorption processes based on these materials are at laboratory scale.

Activated carbon can filter out gaseous pollutants in air. Activated carbon is a conventional method of air purification. Other common methods for air purification are High Efficiency Particulate Air (HEPA) filters, electrostatic smoke precipitators and UV light. More modern methods for air



purification are photochemical materials, soy proteins, transparent PAN polyacrylonitrile (PAN) filters and silk nanofibrils. These methods are described by Roy et al. (Roy, Mishra, Jain, & Solanki, 2018).

The potential of substitution of activated carbon by alternative products as a decarbonisation option should be further analysed by determining the emission intensity of the respective production processes.

## 6 Discussion

This chapter discusses the feasibility of the decarbonisation options for the activated carbon industry in the Netherlands. Cabot Norit Nederland B.V. produces activated carbon in Zaandam and Klazienaveen. The production capacity in the Zaandam plant is small in comparison with that of the Klazienaveen plant. Moreover, the plant in Zaandam has lower greenhouse gas emissions and does not participate in the EU Emissions Trading System. Therefore, this report only focuses on the production process and decarbonisation options for the Klazienaveen plant.

Spent activated carbon with accumulated contaminants inside can be regenerated. This reduces the energy and feedstock consumption. In the Cabot Zaandam plant, spent activated carbon is regenerated through a thermal activation process. According to Cabot, the CO<sub>2</sub> released in the reactivation process amounts to approximately 20% of the emissions released during manufacturing of virgin granular activated carbon. This process requires 10% of virgin activated carbon (Cabot Corporation, 2021).

The main decarbonisation options analysed for the activated carbon manufacturing process are the substitution of raw materials by biomass-based raw materials, energy efficiency improvements and carbon capture technology. Alternative products can substitute activated carbon in various applications.

In the Klazienaveen plant, the most important raw material is currently peat, followed by lignite and coconut shells. Activated carbon can be made from a large variety of raw materials, including wood and agricultural waste materials. The substitution of fossil raw materials by biomass-based raw materials may be limited by the required quality and specifications of the activated carbon that is produced. The use of alternative raw materials may result in a more expensive product.

The plant in Klazienaveen has been an activated carbon producer for a century (Henning & von Kienle, 2010). The plant has improved its energy efficiency by reusing heat that is produced in its production process. The process can be modernized to reduce energy losses in the long rotary kilns. Energy can also be saved by using peat with a lower moisture content. Electricity can be saved by using more efficient electromotors or by replacing the current lighting by LED lighting. The waste gas released in the kilns is rich in carbon monoxide and hydrogen. These gases could be used more efficiently if they were separated from the waste gas stream. The effect of these options on the greenhouse emissions has not been quantified in this report. Such improvements can be realized on relatively short term, but will not lead to full decarbonisation in the long term.

Post-combustion carbon capture is a mature technology that could be used to capture the CO<sub>2</sub> from the flue gas. This option requires substantial investments. In case that the carbon capture unit would be implemented in addition to the substitution of fossil raw material by biomass-based raw materials the CO<sub>2</sub> emissions may become negative. In order to store or use the CO<sub>2</sub> elsewhere (for example in the greenhouse horticulture locations in Klazienaveen and Erica), the CO<sub>2</sub> needs to be transported.

Finally, activated carbon can be substituted by alternative products, which include conventional and non-conventional adsorbents. Non-conventional 'green' adsorbents are not yet used on industrial scale. The non-conventional materials are abundantly available in nature and inexpensive, but the adsorption processes based on these materials are at laboratory scale. The emission intensity of alternative products has not been analysed in this report.

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