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DECARBONISATION OPTIONS FOR THE DUTCH MALTINGS & BREWERIES

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MIDDEN

Manufacturing Industry Decarbonisation Data Exchange Network

Decarbonisation options for the Dutch maltings and breweries
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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 Energy Transition Studies. 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), Dick.vanDam@pbl.nl or S. Gamboa Palacios (TNO), silvana.gamboa@tno.nl.

Erratum
In this version the following correction has been made: In paragraph 1.6, Figure 5, page 15, a value has been corrected from 0.33 to 0.0325 tonne of Waste grains (culms).

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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 Studies has a twofold mission: to accelerate the energy transition and to strengthen the competitive position of the Netherlands. TNO conducts independent and internationally leading research and we stand for an agenda-setting, initiating and supporting role for government, industry and NGOs. The information as presented in this report is (mostly) gathered through desktop research and public sources. During the assessment of the current situation of the maltings and breweries sector and its options for deep decarbonisation, several stakeholders from the sectors were consulted. PBL and TNO remain responsible for the content. The decarbonisation options and parameters are explicitly not verified by the companies. The visions provided in this report do not necessarily represent the sectors' vision on pathways for deep decarbonisation. Furthermore, the insights and data in this report are considered as dynamic and therefore can be changed and adapted when new insights and information becomes available.

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Summary

MIDDEN (Manufacturing Industry Decarbonization Data Exchange Network) aims to support industry, policy makers, analysts and the energy sector in their common efforts to achieve deep decarbonisation. The scope in MIDDEN are Dutch companies in the EU Emissions Trading System (EU ETS) and the direct emissions per production location (i.e. scope 1 only). This report covers two maltings and four breweries that are in the EU ETS, which were responsible for 142 kilotonne (kt) of CO_2 emissions in 2019 (0.17% of the total Dutch EU ETS emissions). The two maltings covered approximately 80% of the total malt production capacity in the Netherlands and the breweries are responsible for 90 – 95% of all the beer produced in the Netherlands.

The two maltings have a combined capacity of approximately 400 kilotonne of malt per year and the four breweries produced approximately 25 million hectolitre of beer in 2019. The average specific energy consumption (SEC) of the two maltings was 2,257 MJ/tonne of malt in 2019 (627 kWh/tonne of malt). The average SEC of the four breweries is estimated to be 73.6 MJ/hectolitre (52.0 thermal energy and 21.6 electrical energy). When comparing SEC-values that are found in the literature with the SEC values of the maltings and breweries, the conclusion can be made that they approach the best practice-values.

In the last few decades, significant effort has been done by the maltings and breweries to increase energy efficiency and increase the share of renewable energy. Both for the maltings and the breweries holds that in the last decades most investments were made in energy efficiency measures and that there is limited potential to further improve the energy efficiency. The large quantities of emissions involved with malt and beer production all come from the combustion of natural gas in direct-fired heating systems, on-site boilers or combined heat-and-power (CHP) installations. Mostly, steam is the heat transfer medium, while some sites have hot water piping systems. For deep decarbonisation therefore, most of the potential relates to replacing natural gas, i.e. the renewable supply of heat and electricity. Some maltings and breweries in the Netherlands have the ambition to become climate neutral before 2030, thus implying that further decarbonisation involves investments in so called ‘break-through’ technologies, such as geothermal energy or (waste) heat networks combined with heat pumps. Furthermore, the use of biogas is important as a substitute of natural gas. Using spent grains, which are left over after de-culming in maltings or after the wort production phase in breweries, as a bio based fuel can be a very valuable decarbonisation measure as well as generating biogas via the anaerobic fermentation of the wastewater treatment systems.

FULL RESULTS

Introduction

This report describes the current situation for the production of malt and beer 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). The MIDDEN project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. The scope in MIDDEN are Dutch companies in the EU Emissions Trading System (EU ETS) and the direct emissions per production location (i.e. scope 1 only[1]). The MIDDEN project will update and elaborate further on options in the future, in close connection with the industry.

The two EU ETS maltings and four EU ETS breweries covered in this report were responsible for in total 142 kilotonne (kt) of CO_2[2] emissions in 2019 (which was 0.17% of the total Dutch EU ETS emissions). The locations of the maltings and breweries and the associated CO_2 emissions (2019) are presented in Figure 1.

Figure 1. Location of Dutch EU ETS maltings and breweries and corresponding scope-1 CO_2 emissions in 2019 (sources: (NEa, 2020; Royal Swinkels Family Breweries N.V., 2021)). Note that the emissions at the breweries also include the emissions associated with soda drinks production.

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[1] The emissions under scope 1 are the direct emissions on-site. Scope 2 emissions are related to imported electricity and scope 3 emissions are emissions in the whole supply chain.

[2] It would be more correct to write CO_2-*equivalents* since the EU ETS is about greenhouse gas emissions. However, for readability reasons, we will refer to just *CO_2* emissions in this report.

In Figure 2 an overview is given of the total emissions per year in the malting and beer sector since 2013 as reported by the Dutch Emission Authority (NEa). The figure clearly shows that the sector structurally reduced emissions each year until 2017, but after 2017 the emissions increased. This is mainly due to the expansion of most of the breweries and the vast increase in capacity by Holland Malt. Furthermore, it is important to note that the total amount of free emission allowances[3], that are granted by the NEa, are reduced structurally each year.

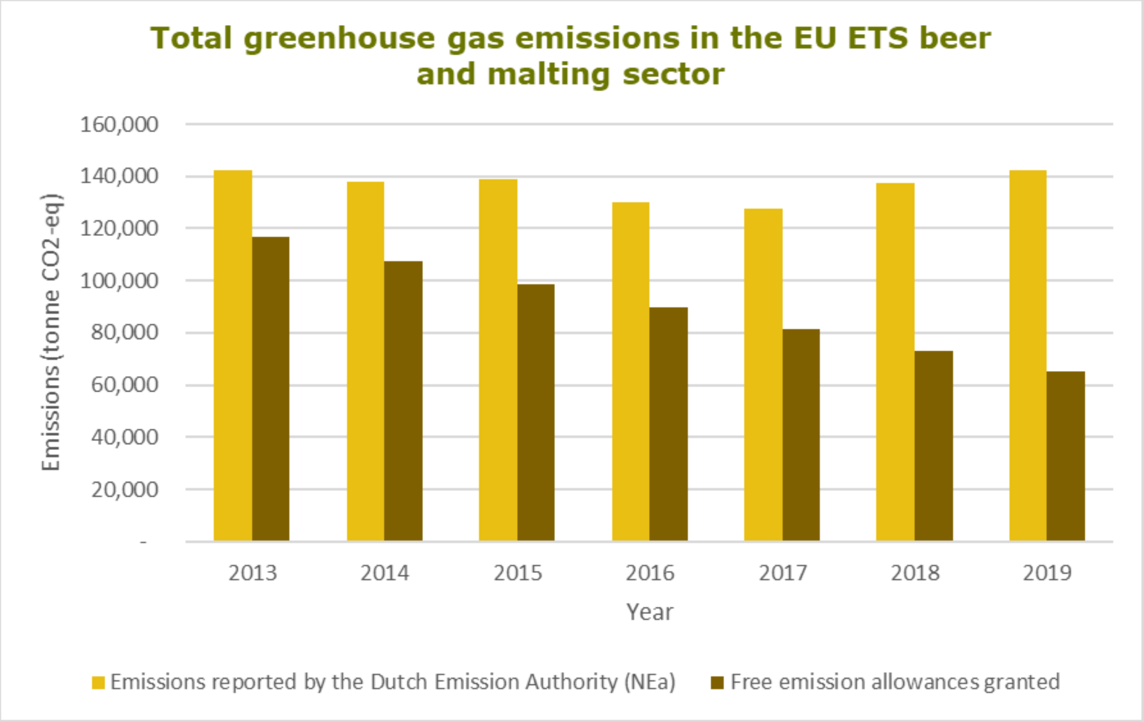

Figure 2. Reported emissions and total free emission allowances granted by the NEa for the whole EU ETS malting and beer sector per year (NEa, 2020).

Reading guide

The report is structured as follows; Chapter 1 and Chapter 2 provide an overview of the current situation for maltings and breweries, respectively, elaborating on the history, production (capacity), process steps, employment, energy use, and CO_2 emissions of the production locations.

In chapter 3, the options for (deep) decarbonisation are discussed for the maltings and breweries in a combined fashion focusing on energy efficiency and utilities. In chapter 4, the current and future decarbonisation measures and plans of the maltings and breweries are presented and the findings from the MIDDEN study for the maltings and breweries section are discussed.

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[3] 1 EUA (European Union Allowance) = The right to emit 1 tonne of CO_2-eq emissions

1 Malt production in the Netherlands

1.1 Maltings in the Netherlands

Malt is produced in many countries in the European Union (EU). As presented in the figure below, the total production capacity in 2019 of all EU countries (including the United Kingdom) together adds up to almost 10 megatonne of malt. The Netherlands is responsible for 5% of the EU total and there are currently four maltings with a total production capacity of about 500 kilotonne (kt) malt per year. These four maltings are *Cargill B.V.* (Swalmen); *The Swaen* (Kloosterzande); *Holland Malt B.V. Lieshout*; *Holland Malt B.V. Eemshaven*. Of these four only two maltings, the ones owned by *Holland Malt B.V.* (locations Lieshout and Eemshaven, are part of the EU Emission Trading Scheme (EU ETS) and are therefore covered in this underlying study. These two maltings cover approximately 80% of the total malt production capacity in the Netherlands. The CO_2 emissions[4] related to the production of these maltings cover about 0.06% of the total EU ETS emissions in 2019 in the Netherlands.

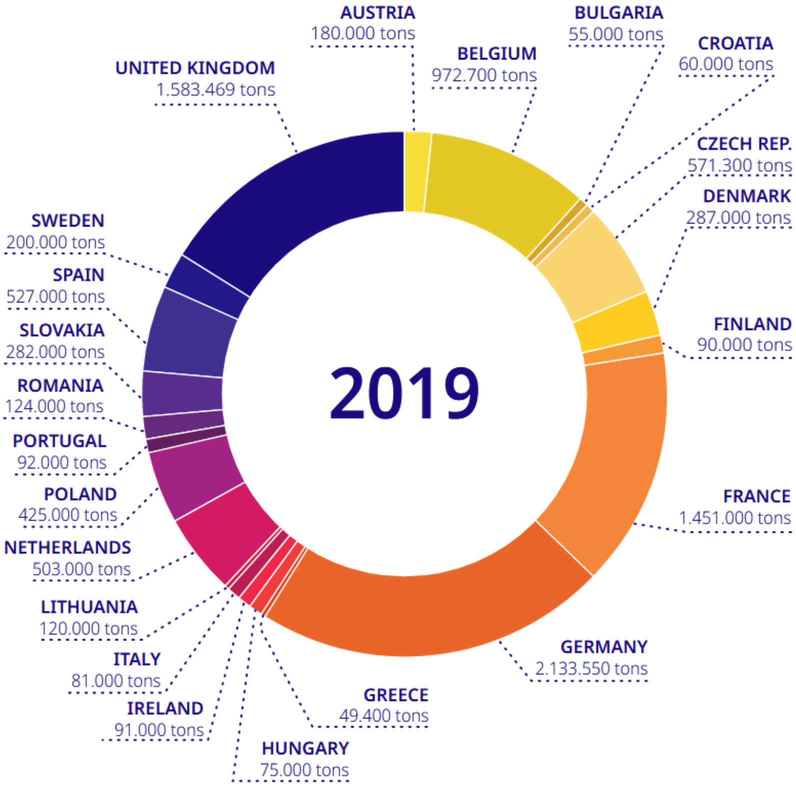

Figure 3. Production of malt in the EU (including the United Kingdom) in 2019. Source: (Euromalt, n.d.)

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[4] Note that with regard to greenhouse gas emissions, only the CO_2 emissions are of interest at maltings.

1.1.1 Holland Malt B.V. maltings

In 2003, *Bavaria* (57%) and *Agrifirm* (43%) joined forces in Holland Malt B.V. In 2014 however, the firms agreed that Agrifirm will sell all their shares to Bavaria, making Bavaria the only shareholder of the Holland Malt maltings (Agrifirm, 2014). Since Bavaria is owned by the *Royal Swinkels Family Brewers Corporation* the two maltings are currently owned for 100% by Royal Swinkels Family Brewers Corporation. In 2016, approximately 50% of the malt production of Holland Malt B.V. was intended for the European market of which part is consumed by Bavaria's own breweries, and the other 50% was exported to Africa, Asia, and Latin-America (Groningen Seaports, 2016). The net revenue of Holland Malt B.V. related to the production of malt was 90 million euros in 2016 and 87.3 million euros in 2017 which covers approximately 15% of the total net revenues of Swinkels Family Breweries (Royal Swinkels Family Brewers Holding N.V., 2020a).

Holland Malt Lieshout

The malting in Lieshout was constructed during the beginning of the second World War by the Swinkels family with a capacity of about 6 kt of malt per year (Holland Malt, 2019). The capacity doubled in 1964 to 12 kt malt per year, and in 1988 the whole unit was modernized and capacity was further extended to 120 kt/year. In 1990 the unit was extended with a second germination tower and in 1995 with a second kilning tower that further increased the production capacity. In the table below, several specifications of the malting are presented. It should be noted however that the malting is not mentioned separately by the Netherlands Emission Authority (NEa) because it is part of the whole production facility site of Bavaria N.V. in Lieshout, which also includes beer and soda drinks production. Therefore, the company name of the malting as reported by the NEa is Bavaria N.V. Furthermore, it should be noted that the utilities/energy system of the malting in Lieshout is shared with the Bavaria facilities that are used for the beer and soda drinks production.

Table 1. Company characteristics of the Holland Malt Lieshout malting

	Value	Source
Company Name (NEa)	Bavaria N.V.	(NEa, 2020)
Subsector (SBI)	11.06	(CBS, 2018a)
Corporate Group	Royal Swinkels Family Breweries N.V.	(NEa, 2020)
Address	De Stater 1, 5737 RV, Lieshout	Company website
Permit number (NEa)	NL-200400297	(NEa, 2020)
Year of Construction	1938	Company website
Employment (fte)*	793	(Royal Swinkels Family Brewers Holding N.V., 2020a)
Website	www.hollandmalt.com	
Production capacity (tonne/yr)	Unknown	
Production of malt in 2019 (tonne)	121,229	(Royal Swinkels Family Breweries N.V., 2021)
CO_2 emissions (scope 1) in 2019 (tonne)	12,828**	(Royal Swinkels Family Breweries N.V., 2021)
Main heat production unit(s)*	Gas-fired CHP('s) Gas-fired boiler(s) CHP biogas motor(s) (BGG's) Waste heat buffer(s)	(Royal Swinkels Family Breweries N.V., 2021)

	Value	Source
Characteristics heat*	Steam: 180 °C, 10 barg Hot water: 95 °C	(Royal Swinkels Family Breweries N.V., 2021)

* Value(s) for the whole Royal Swinkels Lieshout location.

** The total CO_2 emissions (scope 1) of the Lieshout location amount to approximately 47 kt (47,289 ton, (NEa, 2020)), of which 12,828 ton CO_2 can be allocated to the malting processes and 31,357 ton CO_2 to the brewing processes according to Royal Swinkels (Royal Swinkels Family Breweries N.V., 2021). Which leaves approximately 3.1 kton CO_2 that is allocated to other activities like soda production.

Holland Malt Eemshaven

Holland Malt extended its malt production capacity in 2004 by investing in a new malting unit in the Eemshaven region (Holland Malt, 2019). It is a state-of-the-art unit and considered to be one of the largest and modern malt plants of today. In 2018, the malting had a large upgrade and the capacity was doubled to 280 kt of malt with the investment of a second malting facility that took approximately 2 years to be finalized. Holland Malt has the ambition to make this unit the largest and most sustainable maltings in Europe.

Table 2. Company characteristics of the Holland Malt Eemshaven malting

	Value	Source
Company Name (NEa)	Holland Malt B.V. locatie Eemshaven	(NEa, 2020)
Subsector (SBI)	11.06	(CBS, 2018a)
Corporate Group	Royal Swinkels Family Breweries N.V.	(NEa, 2020)
Address	Westlob 4, 9979 XJ, Eemshaven	Company website
Permit number (NEa)	NL-201100008	(NEa, 2020)
Year of Construction	2004	Company website
Employment (fte)	28	(Royal Swinkels Family Brewers Holding N.V., 2020a)
Website	www.hollandmalt.com	
Production capacity (tonne/yr)	280,000	(Royal Swinkels Family Brewers Holding N.V., 2020b)
Production of malt in 2019 (tonne)	280,000	(Royal Swinkels Family Brewers Holding N.V., 2020b)
CO_2 emissions (scope 1) in 2019 (tonne)	33,294	(NEa, 2020)
Main heat production unit(s)	Direct gas combustion	(Royal Swinkels Family Breweries N.V., 2021)
Characteristics heat	Direct gas combustion per installation including heat exchangers	(Royal Swinkels Family Breweries N.V., 2021)

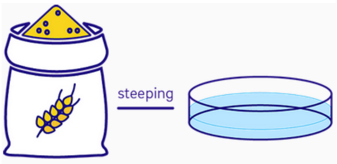
The following subsections describe how malt is produced, providing an overview of the main process inputs and outputs. In addition, where relevant, comparisons with international literature are made. Also, the processes that lead to direct CO_2 emissions are discussed.

1.2 Production of malt in general

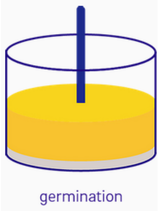
The process of the malt production, which is a batch process and therefore discontinuous, is schematically presented in Figure 4 and entails the following steps (Carbon Trust, 2011a):

1. **Raw barley pre-processing**
   The pre-processing phase covers the intake, drying, storage and screening and weighing of the raw barley. This step covers approximately 4% of the total electricity use and 0.2% of the natural gas use and in total 0.7% of the total primary energy use[5] in maltings.

2. **Steeping**
   First stage of the core malting process is the steeping process that takes about 1-2 days in total (Holland Malt, 2019). During this process the barley is soaked in water to increase the moisture content (from around 12% to 43-46%) and to clean the barley. When the barley starts to sprout, it enters the germination process. The steeping step only needs electricity, mainly for the fans and blowers, and uses approximately 4% of the total electricity consumption and in total 0.6% of the total primary energy use in maltings.



3. **Germination**
   During germination the steeped barley is allowed to sprout in a moist, warm and light environment. The moist barley is spread out in a germination vessel and produces heat during the germination process. For optimal temperature control throughout the bed of barley, and for the grains not to entangle, the bed is turned every so often. At Holland Malt this is done by mechanical turners. This process takes 5 to 6 days in total (Holland Malt, 2019). The germinated barley, also referred to as 'green malt' is then transferred from the germinating vessels to the kiln. The germination step also only needs electricity and uses approximately 30% of the total electricity consumption and in total 4.3% of the total primary energy use in maltings.



4. **Kilning**
   The kilning process is the most important step, since it is crucial for the taste of the beer, and it is also the most energy intensive step in the production of malt. During the kilning process, the germination process is put to a halt by drying the green malt where the temperature is gradually increased up to approximately 100 °C. The malt is stabilized by reducing the moisture content of the green malt to about 3 - 6.5% that also helps to safely store the malt. The kilning process generally takes about a

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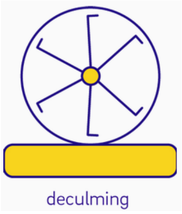
[5] The assumption is made that all of the electricity that is used is imported and all the natural gas use is combusted (direct-fire) to produce heat and not used for electricity production. Therefore, from a malting perspective, electricity can be considered a primary energy source.

day. This step covers approximately 58% of the total electricity use and 99.8% of the natural gas use and in total 93.8% of the total primary energy use in maltings.

5. **De-culming**
   In the final stage, the rootlets of the malt (called culms) are removed and sold as animal feed. This step also only needs electricity and uses approximately 4% of the total electricity consumption and in total 0.6% of the total primary energy use in maltings.



Source pictures above: (Euromalt, n.d.)

Below, a schematic overview of the production process is presented.

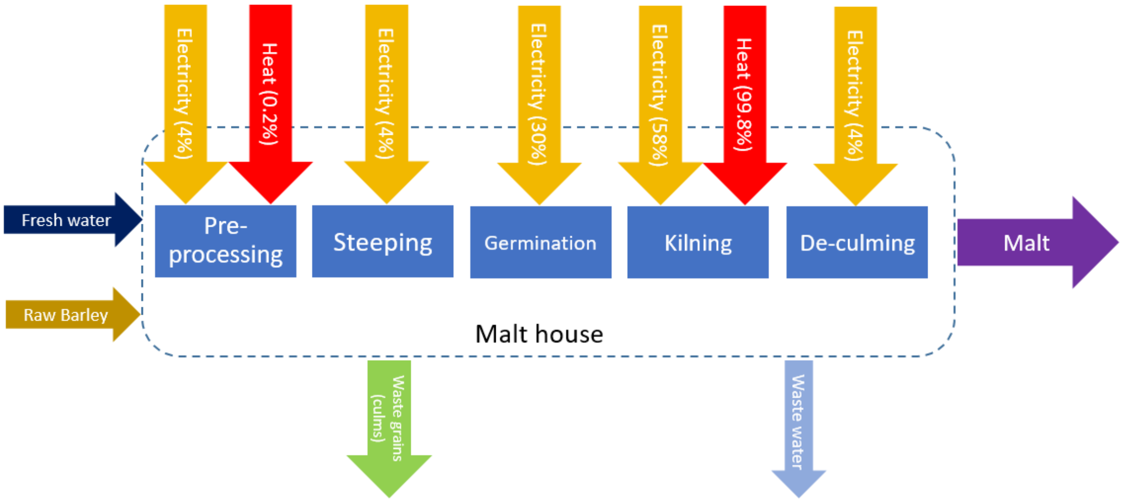


Figure 4. Production of malt

1.3 Energy consumption of Dutch EU ETS maltings

As described in the previous paragraph, 99.8% of the natural gas is used for heating in the kilning process which leaves 0.2% of natural gas to be used in processing the raw barley for drying in the first stage of the malt house. Alongside, approximately 58% of the total electricity consumption is consumed in the kilning process. What becomes clear therefore, is that *the kilning process* is undoubtedly the most energy intensive step in the malt house.

The total energy use of the Holland Malt Lieshout malting[6] in 2019 is estimated to be 241 TJ[7] and the total energy use of the Holland Malt Eemshaven malting was 707 TJ respectively (Royal Swinkels Family Brewers Holding N.V., 2020a). Considering the malt production values of 2019 (121,229 tonne at the Lieshout malting and 280,000 tonne at the Eemshaven malting), the specific energy consumption (SEC) in 2019 is estimated to be 553 kWh/tonne malt (1,990 MJ/tonne) at the Lieshout malting and 701 kWh/tonne malt (2,525 MJ/tonne) at the Eemshaven malting.

Comparison with abroad

The malt house of the Danish Malting Group (DMG) in Denmark, that has a comparable production capacity (115 – 125 kt malt/yr) as the Holland Malt Lieshout malting, claims to be one of the most energy efficient maltings in the world (Danish Energy Agency, 2015). The electricity consumption has been reduced from 145 kWh/tonne of malt in 1997 to 83 kWh/tonne of malt (299 MJ/tonne malt) in 2014 and the heat consumption has been reduced from 820 kWh/tonne of malt to 571 kWh/tonne of malt (2,056 MJ/tonne malt)[8].

In 2011, Carbon Trust (a not for dividend private research company in the UK) analysed the UK's malting sector (Carbon Trust, 2011a). The study covered 27 malting sites in the UK which had a combined production of 1.5 million tonnes (1,500 kt) of malt in 2008/2009. They calculated a weighted average SEC of 961 kWh/tonne of malt (3,460 MJ/tonne of malt) with a relatively large range (between 800 and 1400 kWh/tonne) between the sites. Note however, that this data is now approximately 10 years old and it is highly probable that the average SEC is currently lower.

Considering the former mentioned data on SEC's at other breweries (abroad), it becomes clear that both of the Holland Malt maltings, and especially the Lieshout malting, could be considered a facility with relatively low SEC's.

1.4 CO_2 emissions of Dutch EU ETS maltings

The total scope 1 emissions, related to the emissions at the production site only, for Holland Malt Eemshaven are provided by NEa (2020) and amount to 32,294 tonnes CO_2 in 2019 (= 119 kg CO_2/tonne malt). The total scope 1 emissions for Holland Malt Lieshout were provided by Holland Malt (personal communication) since the NEa only provides scope 1 emissions for location Lieshout as a whole (including production of beer, malt and soda drinks). The CO_2 emissions related to the production of malt only were estimated to be 12,828 tonnes CO_2 (= 106 kg CO_2/tonne malt) in 2019. The main reason why Lieshout has a smaller carbon emission intensity could be due to recent decarbonising measures that were implemented on the site and due to the fact that this malting has scaling and infrastructure advantages compared to the Eemshaven malting, since it is on the same site as the Bavaria brewery.

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[6] This malting uses electricity and heat from the utilities at the Lieshout site (see Table 1). Since Royal Swinkels does not clarify in their annual report whether the reported total energy use is final or primary energy use, we assume that the electricity is 'imported' and the heat originates from the direct combustion of natural gas.

[7] A total energy consumption of 673.5 TJ in 2016 at the Lieshout site, excluding Holland Malt, is reported in the annual report of 2017. The reported energy consumption at the Lieshout site in 2017 was 914.7 TJ and includes Holland Malt. Assuming that there were no significant changes in the energy consumption at the Lieshout site between 2016 and 2017, the difference is assumed to be the energy use at Holland Malt Lieshout. This 2017 number is probably similar to the 2019 number since there was no change in malting capacity during these years.

[8] Note that the majority of the reduction of the electricity consumption per tonne of malt took place between 1997 and 2004 and has been relatively stable after that. The heat consumption per tonne of malt seems to stabilize after 2010. The volatility of the average energy consumption per tonne of malt after the stabilisation is most likely related to the differences in climate each year.

Compared with the energy efficient malt house of the Danish Malting Group (DMG) in Denmark (see previous paragraph), which has a carbon intensity of 129 kg CO_2 per tonne of malt, the Dutch EU ETS maltings have a relatively low carbon intensity (Danish Energy Agency, 2015).

Scope 2 emissions could not be provided since no data was available on the amount of electricity that is used from the grid.

1.5 Malting products and use

Malt, the main product of maltings, is mainly produced for the breweries and distilleries. Since malt is produced from raw barley, the price of barley is the main determinant for the market price of malt. The price of malt also depends on the type of malt produced, but pilsner malt is the default. The following components determine the market price for malt (Carbon Trust, 2011a):

- Costs of raw barley (40-60% of price of malt)
- Costs of energy (6-15% of price of malt)
- Added value/mark-up (investments, labour costs, profit margin etc,) (about 40% of price of malt).

In Table 3 the market price ranges of the input and output products of the maltings are presented.

Table 3. Input and output products of maltings and (market) price ranges

Products	Price (€/tonne)	Country	Source	Comment
		Input		
Raw Barley	185	Netherlands	(Nieuwe Oogst, 2020)	Market prices (week 52, 2020) established at two different markets: in Groningen and Middenmeer
	199	EU-27	(European Commission, 2020)	Average monthly price of November 2020 for the current composition of 27 EU Member States
		Output		
Malt (not roasted)	468*		(Statista, 2020)	Average sales price of malt in 2019 in €$_{2020}$ per ton manufactured in the United Kingdom**
Waste grain (culms)	150 – 200 (avg.: 175)		(Van Iersel, 2018)	Also in line with Carbon Trust (2011a): 125 £$_{2011}$/tonne is approximately 162 €$_{2019}$/tonne***

* Calculated with an exchange rate of 1 GBP = €$_{2020}$ 1.125. Source: https://www.ofx.com/en-au/forex-news/historical-exchange-rates/yearly-average-rates/.

** In the UK the sales prices for malt varied from 2008 to 2019 between 325 euro$_{2020}$/tonne in 2010 to as high as 468 euro$_{2020}$ per tonne in 2019, with an average price of 392 euro$_{2020}$/tonne in the period between 2009 and 2019.

*** Taking into account an exchange rate of 1 GBP$_{2011}$ = €$_{2011}$ 1.15258 and an inflation rate of the Euro of 2% per year from 2011 to 2019.

Raw barley can be bought in the Netherlands or abroad. There are different kinds of barley that can be cultivated; the maltings mostly require specialized malting barley. Of the approximately 30,000 hectares of barley that is cultivated in 2019 in the Netherlands, an average of about 50 percent is malting barley (Nieuwe Oogst, 2019). Malting barley is mainly cultivated in the northern parts of the Netherlands. However, Holland Malt imports raw barley from abroad as well, since Dutch barley is not enough to cover the production volume of Holland Malt. Large volumes of raw malting barley is therefore imported from, among others, Sweden, Denmark and France.

The market for malt and barley decreased in 2020 due to the COVID-19 crisis, since demand for beer fell (Inside Beer, 2020). Market experts say that due to this, farmers and maltings will probably sell their surplus as animal feed during this season, which could mean a shortage of malt and barley in the long run.

According to Holland Malt, approximately 530 kt of barley is needed to produce their maximum yearly output of around 400 kt of malt, which means that there is a certain amount of waste products (for instance culms). Culms are highly valued by maltings since it can be sold as animal feed. It is not accurate to state that there will be as much culms as the difference between input and output (considering for instance that the barley input has a higher moist percentage than the malt output), but a certain amount of waste-product is left over to be re-used or sold. According to Holland Malt, this adds up to about 13 kt of waste-products per year.

Furthermore, water is used at the maltings, mainly during the steeping process. The Holland Malt breweries used 3.25 m^3 of water per tonne malt (average of the two maltings) in 2019 (Royal Swinkels Family Brewers Holding N.V., 2020a). Most of the used water will flow off to the wastewater treatment.

1.6 Mass and energy balance

For the mass and energy balance we assumed for the energy consumption the average of the SEC's of the two maltings: 627 kWh/tonne of malt (electricity + heat). A schematic overview of the malting process is presented in Figure 5. As displayed in the figure, it is assumed that the needed heat is produced by either a combined heat and power installation (CHP), by bio-CHP(s), by a natural gas boiler, or by direct combustion of heat, since this is different at the two breweries.

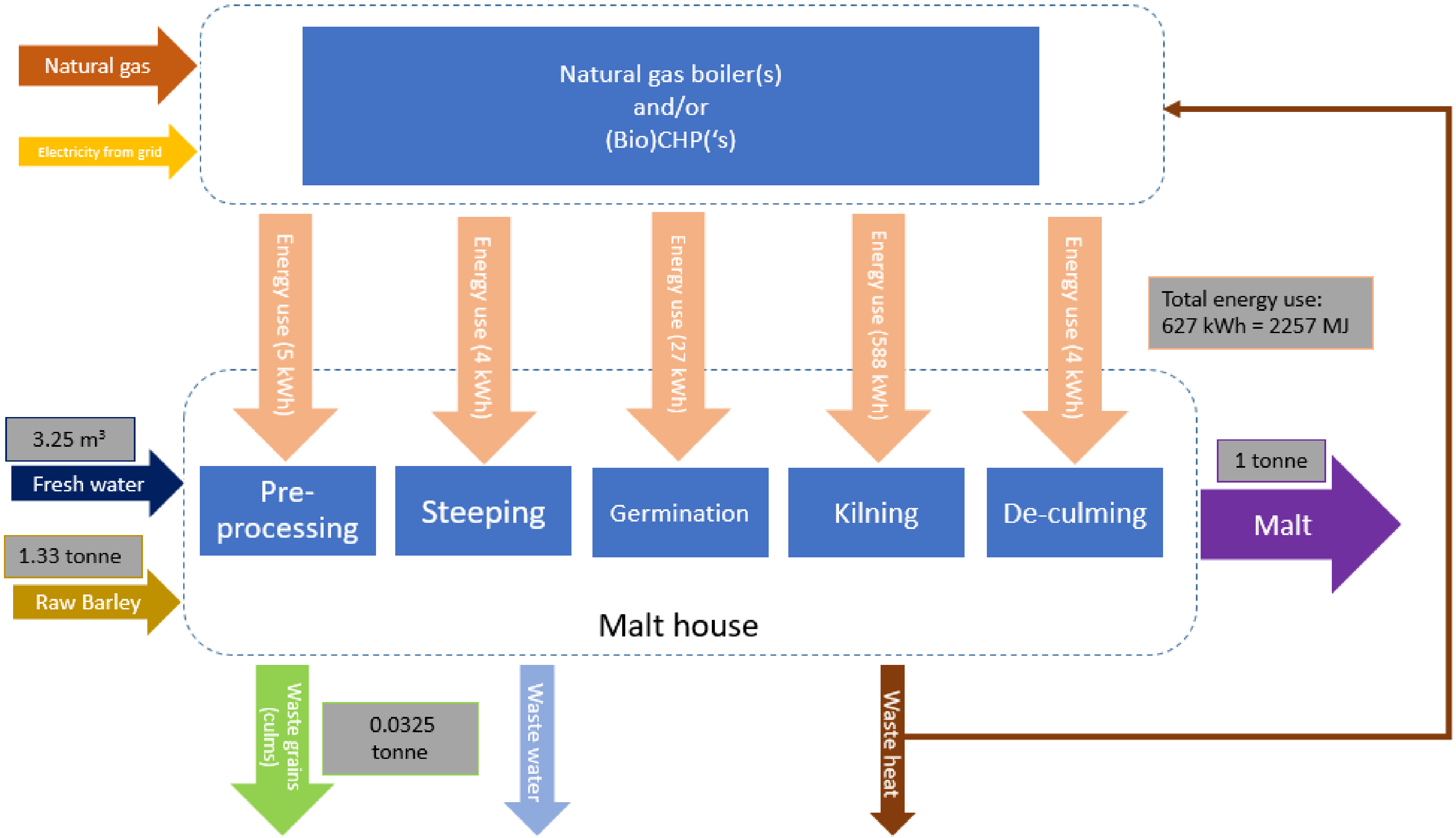

Figure 5. Mass and energy balance of malt production in Dutch EU ETS maltings

2 Beer production in the Netherlands

2.1.1 Breweries in the Netherlands

In 2017, around 370 breweries were active in the Netherlands (CBS, 2017). In 2017, the total production volume in the Netherlands was roughly 27 million hectolitres (hl)[9] and the Netherlands was, with a production value of 2.5 billion euros, the fifth largest beer producer in Europe (CBS, 2018b).

Four of the 370 breweries are currently part of the EU ETS. These four breweries produced approximately **25 million hectolitres in 2019**[10] and are therefore responsible for more than 90% of the total Dutch production volume yearly. The four EU ETS breweries were responsible for approximately 93,196 tonnes of CO_2 in 2019, which is approximately 0.1% of the total Dutch EU ETS CO_2 emissions (NEa, 2020). The Dutch breweries belong to the top 10% most energy and water efficient breweries worldwide (RVO, 2016). Nonetheless, reducing CO_2 emissions in this sector is one of the main challenges and ambitions of the breweries for the coming decade(s). The main reasons to drive down CO_2 emissions are: increasing energy prices, concerns about security of energy supply, and (more stringent) climate change legislation (Andrews, et al., 2011). Most of the EU ETS breweries currently in the Netherlands have the ambition to become climate neutral before 2030.

Background information and plant characteristics of all the breweries are presented in the following paragraphs.

2.1.2 Heineken Zoeterwoude

Heineken beer was originally founded in Amsterdam by Gerard Adriaan Heineken (Heineken, n.d.). In 1867, a new brewery opened in Amsterdam followed by another brewery Rotterdam in 1873. After the opening in 1975 of Heinekens' largest Brewery in the Netherlands in Zoeterwoude, the breweries in Amsterdam and Rotterdam closed down. Since 2017, the production volume of Heineken Zoeterwoude is approximately 10.4 million hl (Kempers, 2018). The brewery in Zoeterwoude is orientated towards large production volumes, and the majority of the production volume is exported to the Americas and Asia.

Table 4. Company characteristics of Heineken Zoeterwoude

	Value	Source
Company Name (NEa)	Heineken Nederland B.V., brouwerij Zoeterwoude	(NEa, 2020)
Subsector (SBI)	11.05	(CBS, 2018a)
Corporate Group	Heineken Global	(NEa, 2020)
Address	Burgemeester Smeetsweg 1, Zoeterwoude	(Heineken, n.d.)
Permit number (NEa)	NL-200400202	(NEa, 2020)

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[9] 1 hectolitre (hl) = 100 litre

[10] This is the total production volume calculated when the 2019 production volumes of each individual EU ETS brewery, as presented in the tables in the following paragraphs, are added.

	Value	Source
Year of Construction	1975	(Heineken, n.d.)
Employment (fte)	500	(Kempers, 2018)
Website	https://www.heinekennederland.nl	
Production capacity (hl/yr)	Unknown	
Production (2017) (hl)	10.4 million	(Kempers, 2018)
CO_2-emissions (scope 1) in 2019 (tonne)	38,855	(NEa, 2020)
Main heat production unit(s)	Combined Heat and Power (CHP)	Personal Communication
Characteristics heat	180 °C, 10 bar (saturated steam)	Personal Communication

2.1.3 Heineken Den Bosch

Amongst the breweries that are currently in operation in the Netherlands, the Heineken-brewery in Den Bosch - that became operational in 1958 - is the oldest. Between 1995 and 2005, the brewhouse has been renovated and in 2017 the production volume was approximately 6.2 million hl.

Table 5. Company characteristics of Heineken Den Bosch

	Value	Source
Company Name (NEa)	Heineken Nederland B.V., locatie Den Bosch	(NEa, 2020)
Subsector (SBI)	11.05	(CBS, 2018a)
Corporate Group	Heineken Global	(NEa, 2020)
Address	Rietveldenweg 25	(Heineken, n.d.)
Permit number (NEa)	NL-200400227	(NEa, 2020)
Year of Construction	1958	(Heineken, n.d.)
Employment (fte)	400	(Kempers, 2018)
Website	https://www.heinekennederland.nl	
Production capacity (hl/yr)	Unknown	
Production (2017) (hl)	6.2 million	(Kempers, 2018)
CO_2-emissions (scope 1) in 2019 (tonne)	15,428	(NEa, 2020)
Main heat production unit(s)	Combined Heat and Power (CHP) installation	Personal Communication
Characteristics heat production unit	180 °C, 10 bar (saturated steam)	Personal Communication

2.1.4 Grolsch

The Grolsch brewery in Enschede, the latest installed brewery amongst the four EU ETS breweries, started its operations in 2004 in Usselo (municipality of Enschede) and closed down the other two older breweries in Enschede and Groenlo (Grolsch, n.d.). Grolsch is currently part of Asahi-group, that took over the company from SABMiller in 2016. In 2019, Grolsch sold approximately 2.8 million hl of beer which resulted in a 13% Dutch market share in that year (Royal Grolsch, 2020a).

Table 6. Company characteristics of Grolsch

	Value	Source
Company Name (NEa)	Grolsche Bierbrouwerij Nederland BV	(NEa, 2020)
Subsector (SBI)	11.05	(CBS, 2018a)
Corporate Group	Asahi Group	(NEa, 2020)
Address	Brouwerslaan 1	(Grolsch, n.d.)
Permit number (NEa)	NL-200500081	(NEa, 2020)
Year of Construction	2005	(Grolsch, n.d.)
Employment (fte)	702[11]	(Royal Grolsch, 2020a)
Website	https://www.grolsch.nl/	
Production capacity (hl/yr)	Unknown	
Production (2020) (hl)	2.8 million	(Royal Grolsch, 2020a)
CO_2-emissions (scope 1) in 2019 (tonne)	7,556	(NEa, 2020)
Main heat production unit(s)	Unknown	
Characteristics heat production unit	170 °C, 6 bar (saturated steam) 105 °C, 6 bar (hot water)	(Royal Grolsch, 2020b)

2.1.5 Bavaria

Since 1773, the Bavaria-brewery is owned by the Swinkels family. The name 'Bavaria' refers to a type of beer originating from the German federal state 'Bayern' – or, Bavaria in English (BHIC, 2011). This beer-type is bottom-fermented, and is often also referred to as 'pilsner'. In 1934, the brewery in Lieshout started its operations. This facility is currently the largest brewery of Bavaria with a production volume of approximately 5.3 million hl per year (Royal Swinkels Family Breweries N.V., 2021).

Table 7. Company characteristics of the Bavaria brewery

	Value	Source
Company Name (NEa)	Bavaria N.V.	(NEa, 2020)
Subsector (SBI)	11.05	(CBS, 2018a)
Corporate Group	Royal Swinkels Family Breweries N.V.	(NEa, 2020)
Address	De Stater 1, 5737 RV, Lieshout	Company website
Permit number (NEa)	NL-200400297	(NEa, 2020)
Year of Construction	1934	Company website
Employment (fte)*	793	(Royal Swinkels Family Brewers Holding N.V., 2020a)
Website	www.bavaria.com	
Production capacity (hl/yr)	Unknown	
Production 2019 (hl)	5.3 million	(Royal Swinkels Family Breweries N.V., 2021)

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[11] This is direct employment, though not exclusively related to the beer production process

	Value	Source
CO_2 emissions (scope 1) in 2019 (tonne)	31,357**	(Royal Swinkels Family Breweries N.V., 2021)
Main heat production unit(s)*	Gas-fired CHP('s) Gas-fired boiler(s) CHP biogas motor(s) (BGG's) Waste heat buffer(s)	(Royal Swinkels Family Breweries N.V., 2021)
Characteristics heat*	Steam: 180 °C, 10 barg Hot water: 95 °C	(Royal Swinkels Family Breweries N.V., 2021)

* Value(s) for the whole Royal Swinkels Lieshout location.

** The total CO_2 emissions (scope 1) of the Lieshout location amount to approximately 47 kt (47,289 ton, (NEa, 2020)), of which 12,828 ton CO_2 can be allocated to the malting processes and 31,357 ton CO_2 to the brewing processes according to Royal Swinkels (Royal Swinkels Family Breweries N.V., 2021). Which leaves approximately 3.1 kton CO_2 that is allocated to other activities like soda production.

2.2 Production of beer in general

The following subsections describe how beer is generally produced, providing an overview of the main process inputs and outputs. Also, the processes that consume energy and lead to direct CO_2 emissions are discussed. Furthermore, the best practices in brewing are depicted.

2.2.1 Production process of beer

The processes of brewing have remained largely unchanged in the last few decades (Andrews, et al., 2011). The brewing industry and brewing process are characterized by several batch-type operations, where raw materials are converted into a final product (Olajire, 2012). An illustration of the brewing process, from malt to a bottled beer, is given in Figure 6.

Four different overall stages can be found in the beer brewing process. Starting with the first phase, which is the **dry phase**, where malted barley arrives at the brewery and is milled; milling is the crushing of malt to ensure a high yield of extracted substances in the next steps of the beer production process (Galitsky, Martin, Worrel, & Lehman, 2003). The dry phase uses very little electrical energy and no thermal energy. This phase is often aggregated to the brewhouse phase.

The second phase is the **brewhouse phase** where large amounts of steam is needed for heating and boiling purposes. The first step is mixing and heating the milled malt with water. Enzymes in the mash break, due to the heating (approximately 70 °C), starch into sugars such as maltose. When this process is finished, this sweet substance is called (sweet) wort (Galitsky, Martin, Worrel, & Lehman, 2003). Consequently, the wort and the grains present in the wort need to be separated; a mash filter is used to separate the wort into filtered wort and spent grains. Next, the filtered wort needs to be boiled (using steam). Conventional atmospheric boiling takes up to one and a half hours with an evaporation rate between 8 – 12% (Willaert & Baron, 2004). During the boiling, hops are added for bitterness and better taste. Currently, major brewers even reduced the evaporation rate from 7-8% to 4-5% (Andrews, et al., 2011). The vapours contain 99% water and up to 160 organic constituents from hops and malt (Willaert & Baron, 2004). If the vapour with these volatiles (unwanted flavour components) is allowed to leave the chimney, odour pollution is caused (Willaert & Baron, 2004). In summary, wort boiling serves the following purposes: wort sterilisation, wort concentration, wort stabilisation, hop isomerisation and volatile removal (Hardwick, 1994; Andrews, et al., 2011). Furthermore, metal ions, tannin substances and lipids form insoluble complexes, and the soluble substances from the hops are extracted. The boiled wort is then clarified (to ensure efficient fermentation) using a whirlpool (Olajire, 2012).

The third phase is the **cold phase**; this phase starts with the cooling of the wort, to achieve fermentation temperature (Hardwick, 1994). In most modern breweries, the heat that is extracted during cooling is used to pre-heat other processes in the brewery. Then fermentation starts when yeast is added to convert the sugars into alcohol and carbon dioxide. Fermentation takes up a few days for ales and up to 10 days for lagers (Sorrell, et al., 2000; Carbon Trust, 2011b). Fermentation generates significant heat that must be dissipated to avoid yeast damaging (Galitsky, Martin, Worrel, & Lehman, 2003). A centrifuge is used to remove the yeast. Now, the beer is sent to maturation tanks and held at a conditioning temperature of -1 to 10 °C for several days to over a month (Carbon Trust, 2011b). Then, a filter is used to remove any proteins and the beer is sent to the bright, or filtered, beer tanks (Carbon Trust, 2011b). This third phase needs a lot of electricity for cooling and this whole step takes up to two to three weeks (Olajire, 2012).

After maturation and stabilization, the last phase starts, which is the **packaging phase**. Depending on the packaging type and/or bottling line, beer is either first pasteurised and then packed, or first bottled and then pasteurised. Thermal energy (steam or hot water) is needed to pasteurise the product. During pasteurisation, beer is heated to approximately 60 °C (Galitsky, Martin, Worrel, & Lehman, 2003). The aim is to remove all remaining harmful bacteria and stop all yeast activity in the beer.

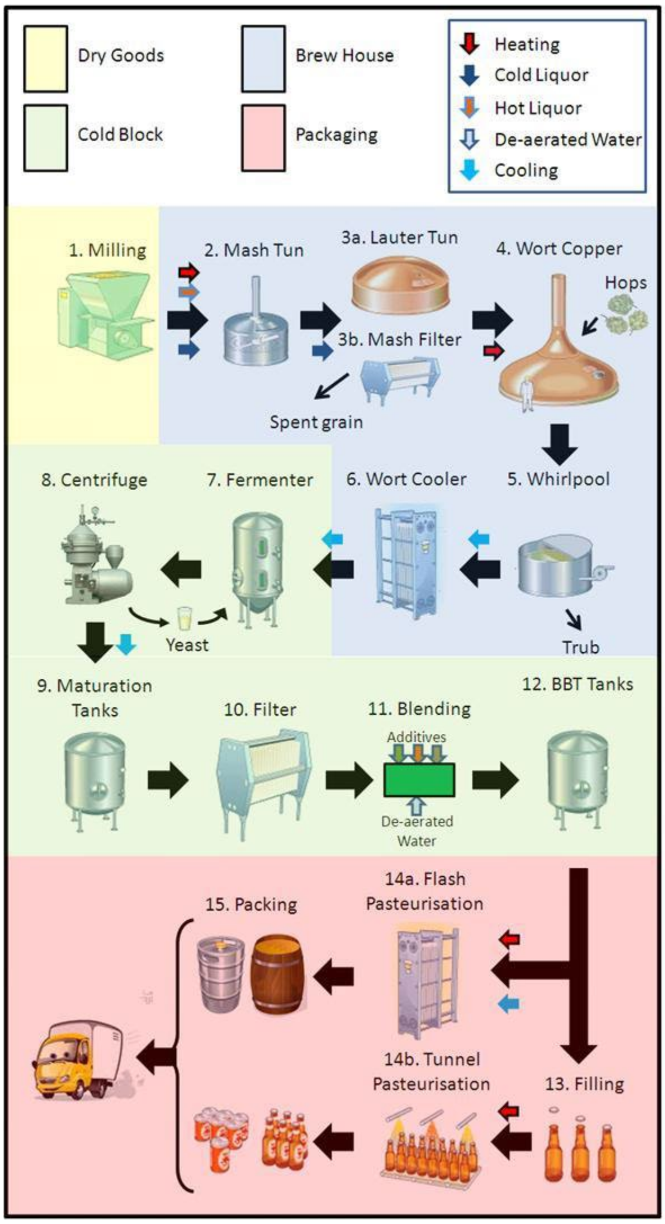

Figure 6: Brewing process diagram. Source: (Carbon Trust, 2011b)

2.2.2 Energy consumption

Energy consumption of breweries can be divided into two different forms; electrical and thermal energy. Thermal energy (at the most breweries in the form of steam, but at some modern breweries hot water could also be used as medium for some processes) is mostly generated in a boiler house or in a combined heat and power (CHP) plant using (natural) gas. This thermal energy is used for wort boiling and water heating in the brewhouse and the packaging hall (Olajire, 2012). The combustion of the natural gas in the boiler house or CHP causes CO_2 emissions. Although most breweries also use the biogas that is produced in de the wastewater treatment plant, large amounts of natural gas is being used to create heat at the four EU ETS breweries. Electrical energy is either bought from the grid or generated on-site with a CHP plant, or in some cases also with solar panels or wind turbines (Carbon Trust, 2011b; European Commission, 2006). Energy costs range between 3 – 8% of total production costs, therefore efficient energy use has become a major factor in the profitability of a brewery, depending on location, size and other variables (Olajire, 2012) (Xhagolli & Marku, 2014).

Various literature on energy use in beer production is available worldwide. Different specific energy consumption (SEC) values are summarised in Table 8. The different studies all focus on large breweries in either Europe or the United States of America.

Table 8. SEC in beer production (in MJ per hl) according to various sources

Source	SEC (in MJ/hl)	Thermal energy (in MJ/hl)	Electrical energy (in MJ/hl)
(Sorrell, et al., 2000)	163	*Not specified*	*Not specified*
(Galitsky, Martin, Worrel, & Lehman, 2003)	300*	*Not specified*	*Not specified*
(Scheller, Michel, & Funk, 2008)**	169.2 – 187.2	129.6 – 144	39.6 – 43.2
(Carbon Trust, 2011b)	135	*Not specified*	*Not specified*
(Olajire, 2012)	155	110	45
(Xhagolli & Marku, 2014)	178.8 – 243.2	150 – 200	28.8 – 43.2
(Giner Santonja, Karlis, Stubdrup, Brinkmann, & Roudier, 2019)	72 – 180***	*Not specified*	*Not specified*

* Value is an approximation since it is derived from a graph. Furthermore the original value is presented in kBtu/barrel and is therefore converted to MJ/hl.
** Value converted from kWh/hl to MJ/hl by multiplying with 3.6
*** Original value: 0.02 MWh/hl – 0.05 MWh/hl, data from different breweries between the years 2012 and 2014.

The two most energy-intensive steps in the **brewhouse** are *mashing* and *wort boiling* (Scheller, Michel, & Funk, 2008; Olajire, 2012; Giner Santonja, Karlis, Stubdrup, Brinkmann, & Roudier, 2019). In both steps a lot of steam is used for **heating**. These two processes account for approximately 50% of steam use (Sorrell, et al., 2000; Willaert & Baron, 2004). *Wort boiling* is identified as the single most energy-intensive step in the whole beer producing process (Galitsky, Martin, Worrel, & Lehman, 2003; Kunze, 2004; Willaert & Baron, 2004). Wort boiling accounts for 20 – 40% of all thermal energy utilised in a brewery (Andrews, et al., 2011).

Energy consumption reduction targets have led to a plethora of approaches to reducing the energy needed for wort boiling, such as a reduction in the evaporation of water (which accounts for up to 60% of the total energy used in wort boiling) (Andrews, et al., 2011). Alternative systems are even developed to remove the volatiles under vacuum, or by steam stripping instead of evaporation, leading to equal volatile reductions combined with lower energy inputs (Andrews, et al., 2011).

The packaging-phase can also be a large user of thermal energy, mainly for pasteurisation and washing of returnable containers, such as kegs or casks (or even bottles, especially in the Netherlands with our national deposit system on glass bottles). The packaging mix impacts the SEC as small packs are known to be more energy intensive than larger volume packs such as kegs (Carbon Trust, 2011b). When looking at returnable bottles, the bottle washer and pasteurisation are the most energy-intensive. With non-returnable bottles, pasteurisation is usually the largest energy consumer in the packaging-phase (Muster-

Slawitsch, Weiss, Schnitzer, & Brunner, 2011). According to Sorrell et al., there is a large range between different types of packaging:

"The SEC for fuel use in packaging can vary from as little as 4 MJ/hl for bulk tanks to 170 MJ/hl for bottles. The fuel use for packaging in kegs, cans, PETs and retail tanks is similar at around 30 MJ/hl. The big fuel user is packaging in bottles." - (Sorrell, et al., 2000, p. 21)

In Table 9, an overview is given of the heat consumption values at different brewery department or processes.

Table 9. Heat consumption (in MJ/hl beer) for different brewery departments/processes (Giner Santonja, Karlis, Stubdrup, Brinkmann, & Roudier, 2019, pp. 306, table 4.1).

Department/process	Minimum	Mean	Maximum	Literature*	Measured**
Brewhouse	87	92	121	84 - 113	50 - 80
Bottling installation	58	86	94	25 - 46	38 - 58
Kegging installation	8	11	13	8 - 13	N/A
Process water	3	4	8	4 - 8	N/A
Service water	N/A	N/A	N/A	8 - 17	N/A
Miscellaneous	N/A	N/A	N/A	33 - 46	95
Total	**156**	**193**	**236**	**162 - 243**	**183 - 233**

* 20,000 to 500,000 hl beer sold/yr
** 300,000 to 500,000 hl beer sold/yr
N/A = no information provided

Most important **electricity consumption** processes are **refrigeration** (44%), **packaging** (20%) and **compressed air** (10%) (Scheller, Michel, & Funk, 2008). Furthermore, there are a lot of small electricity consumers like pumps, ventilators, drives and lighting. Electricity is of less importance during this research, as the focus is on direct on-site emissions (scope 1). However, for a fully decarbonised industry also the indirect emissions from electricity generation should be mitigated.

Considering what has been reported in literature, two main issues are important to keep in mind:

1. The first phase of the production process, milling, does not require significant amounts of energy. Brewhouse and packaging both use large amounts of thermal energy. The cold-phase uses large amounts of electrical energy.
2. The SEC-values found in the literature differ notably (they range between 112 – 300 MJ/hl).

2.2.3 CO_2 emissions

Carbon Trust (2011a) computed a CO_2 breakdown for a typical 2-million hectolitre brewery (comparable to the size of the Grolsch brewery). The two main contributors to CO_2 emissions, as can be seen in Figure 7, are the brewhouse and packaging phase. This follows from the fact that during these two phases, the most energy is used.

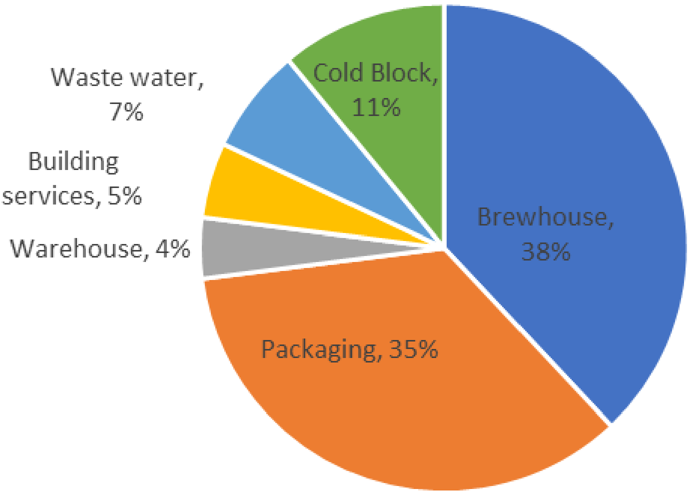

Figure 7. CO_2 breakdown from a typical 2-million hl brewery (Carbon Trust, 2011a, p 11)

2.2.4 Best practices

According to the Reference Document on Best Available Techniques (BAT), or in short the BREF document, for the food, drink and milk industries of the European Commission, the BAT benchmark minimum SEC for beer production is 0.02 MWh/hl of products (72 MJ/hl) (Giner Santonja, Karlis, Stubdrup, Brinkmann, & Roudier, 2019). Scheller et al. researched efficient use of energy in the brewhouse (Scheller, Michel, & Funk, 2008). The most efficient brewery they assessed was a 2.8 million hectolitre brewery in Germany (in size this brewery is comparable to the Grolsch brewery). This brewery needs 54 MJ/hl of thermal energy and 16.2 MJ/hl electrical energy, which adds up to a total SEC of 70.2 MJ/hl. This brewery uses an efficient internal boiler and recovers waste heat through condensation (both explained in the chapter 3), consequently using this as process energy for the heating of wort. However, this brewery only delivers beer in barrels, which is one of the least demanding packaging materials in terms of thermal energy. Energy consumption and related CO_2 emissions of breweries is heavily depending on production volume, pack mix (cans, kegs, tank containers etc.) as well as the number of different beers (SKU number) that are produced.

Muster-Slawitsch et al. developed the “Green Brewery Concept tool”, and focused on small- (20.000 – 50.000 hl/year) and medium-sized (800.000 – 1.000.000 hl/year) breweries (Muster-Slawitsch, Weiss, Schnitzer, & Brunner, 2011). The minimal thermal energy demand is highest for the brewhouse, ranging from 20 – 25 MJ/hl. One of the breweries also filled returnable bottles and had, after all the optimisation measures (such as biogas, from both wastewater and spent grains), a remaining final thermal energy demand of 37 MJ/hl. When using a CO_2-emission factor of 56.6 kg/GJ for natural gas[12], 37 MJ/hl (with an estimated boiler efficiency of 95%), would result in:

$$(0.0566\ kg\ \mathrm{CO_2}/MJ * 37\ MJ)\ /\ 95\% = 2.18\ kg\ CO_2\ per\ hectolitre.$$

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[12] (Blok & Nieuwlaar, 2016)

2.3 Energy consumption of the four EU ETS breweries

The Netherlands Enterprise Agency (RVO) published a report on the energy use of the large Dutch breweries, also including Heineken's Brand brewery in Wijlre (RVO, 2016). The breweries realised a process efficiency improvement of 13.0% between 2009 and 2015. 43% of this improvement was realised along the production chain, and 57% was realised via sustainable energy. In 2015, the breweries' realised primary energy use was 3,266 TJ which was 0.8% lower compared to 2014 while production volumes remained about the same[13]. This is partially due to adaptations and optimization of cooling systems and a different way of lagering, which resulted in a reduction of 19 TJ in the process.

When correcting for the Brand brewery in Wijlre (which is not an EU ETS brewery), based on its share in the total production volume of the five breweries[14], approximately **3,200 TJ of primary energy** (natural gas use at the sites plus electricity and heat imported from external locations) [15] was consumed at the four EU ETS locations in 2015. Of this 3,200 TJ, 66% (2,112 TJ) can be attributed to the combustion of natural gas[16].

The Dutch EU ETS breweries present in their annual reports some information regarding the SEC of their operations (see Table 10). However, it is not always clear how these values were exactly determined, which makes it difficult to compare them. It is for example not clear whether the SEC is expressed in terms of primary or final energy use and whether the energy consumption from all process steps are included or not. Bavaria's value is aggregated and is a weighted average of their breweries in Lieshout, Berkel-Enschot, Bodegraven, Rodenbach (Belgium) and Debre Birhan (Ethiopia) (Swinkels Family Brewers Holding N.V., 2019). The value Heineken gives is the average of the breweries in Zoeterwoude, Den Bosch and the Brand-brewery in Wijlre (part of Heineken-group) (Heineken Nederland, 2016). Furthermore, these values do not specify which forms of energy are used during production and do not describe which parts of the production process are using the most energy. According to TNO expert Anton Wemmers (interview, 2018), the energy intensities of the four production locations should be quite comparable. Hence, we will assume the average of the breweries to be representative for all sites.

Table 10. Specific energy consumptions as stated by the Dutch EU ETS breweries. Note that it is unclear whether the provided SEC-value represent primary or final energy use.

Company	Specific energy consumption (SEC)	Source
Heineken Netherlands Supply	76 MJ/hl in 2015*	(Heineken Nederland, 2016)
Grolsch	84 MJ/hl in 2019	(Royal Grolsch, 2021)
Swinkels Family Brewers	128 MJ/hl in 2019**	(Royal Swinkels Family Brewers Holding N.V., 2020a)
Average	**96 MJ/hl**	

* Average of location in Zoeterwoude, Den Bosch and Wijlre. Later data than 2015 was not available.
** Weighted average of their breweries in Lieshout, Berkel-Enschot, Bodegraven, Rodenbach (Belgium) and Debre Birhan (Ethiopia)

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[13] Note that in this report, RVO counts electricity (which was approximately 35% of the total primary energy use presented) as a primary energy source, while in scientific literature electricity is considered a secondary energy carrier.

[14] With the help of (Kempers, 2018)

[15] RVO refers to primary energy use and does not clarify where the used electricity comes from. Therefore, the assumption is made that the 'electricity use' figure is electricity that is imported and could therefore, from a brewery perspective, be counted as a primary energy source since

[16] It is not stated whether this is the HHV or LHV value, but since mostly steam is generated at the breweries we assume LHV.

When comparing the SEC-values that are found in the literature (see Table 8) with the SEC values as mentioned by the breweries Table 10, the conclusion can be made that the SECs mentioned by the breweries are significantly lower than those that were found in the literature. The Dutch EU ETS breweries even approach the best practice-values.

To further investigate the robustness of the SEC-numbers that has been published by the companies, an interview has been conducted in 2017 with industry expert Anton Wemmers of TNO. Wemmers researched the large Dutch breweries extensively during his career, focusing on the application of heat pumps, heat integration and overall energy reductions. Anton Wemmers examined different data sets he gathered during his different researches and provided this research with some relevant data (see Table 11). In this table, the energy use per hectolitre for large Dutch breweries, in an optimal situation with a normal packaging mix, is presented. Furthermore, Table 11 describes the total energy demand per hectolitre beer, divided in thermal and electrical energy and also further differentiated in the different steps of the production process. All four breweries confirmed the values depicted in Table 11. Relatively small differences occur between locations.

Table 11. SEC per phase for Dutch EU ETS breweries according to Anton Wemmers (TNO)

Energy intensity per phase for Dutch EU ETS breweries according to TNO				
	MJ(*th* or *e*) /hl	% thermal	% total energy demand	
Thermal energy use per process				
Brewing (phase 2)	20	38.5%	**27.7%**	
Fermenting (phase 3)	0	0.0%	**0.0%**	
Packaging (phase 4)	20	38.5%	**27.7%**	*Depends on packaging mix (tunnel pasteurisation has a significant heat demand)*
Other	12	23.0%	**16.3%**	*Heat for buildings, cleaning water, usage CHP*
Total thermal energy use	**52**	**100.0%**	***70.7%***	
Electricity use per process				
Brewing (phase 2)	3.6	16.7%	**4.9%**	
Fermenting (phase 3)	10.8	50.0%	**14.7%**	*Cooling for 80% allocated to fermentation*
Packaging (phase 4)	5.4	25.0%	**7.3%**	
Other	1.8	8.3%	**2.4%**	
Total electricity use	**21.6**	**100.0%**	***29.3%***	
Total	**73.6**		**100%**	

Table 11 also shows much lower SEC-values than the available literature. The phases *brewing* and *packaging* are still the two dominant users of thermal energy, both use approximately 38.5% (thus 77% in total). The *milling* phase (phase 1) is not included, as it is not significant in terms of energy use. *Mashing* and *wort boiling* are the two most thermal energy-intensive steps in the brewhouse. According to Anton Wemmers, the type of packaging, method of pasteurisation and the type of packaging line have a significant influence on the SEC. The proportion between brewhouse and packaging can even be 65% (brewing) and 27% (packaging) for less energy-intensive packaging materials and operating lines. In particular, if cans and bottles are pasteurised using tunnel pasteurisation, the packaging material needs also to be heated during pasteurisation, which leads to increased heat demand.

When taking into account the known production capacities of the breweries, we can calculate the total maximum thermal and electrical energy consumption per brewery, based on the calculations of Anton Wemmers. These results are presented in Table 12. It shows that the total estimated energy use of the breweries combined is approximately 1,818 TJ, which is considerably higher than that reported by RVO (2016): 3,200 TJ of primary energy in 2015. This difference could partially be explained by the fact that RVO reported the total *primary* energy and not the total actual heat and electricity consumed by the breweries. Furthermore, the RVO data (beer production value and energy consumption data) is considerably older than the data of Anton Wemmers and the current production values.

Table 12. Energy consumption per brewery based on the calculations of Anton Wemmers and the most up to date production values

Brewery	Assumed yearly production (hl)	Estimated thermal energy use (TJth)	Estimated electrical energy use (TJe)	Estimated total energy use (TJ)
Heineken ZW	10,400,000	541	225	765
Heineken DB	6,200,000	322	134	456
Grolsch	2,800,000	146	60	206
Bavaria Lieshout	5,300,000	276	114	390
Total	**24,700,000**	**1,284**	**534**	**1,818**

2.4 Brewery products and use

2.4.1 Input

The main raw materials that serve as an input for the production of beer are malt, hops, yeast and water. Mostly, malt is imported from another company, like Holland Malt and not produced on the same site with the exception of the Lieshout site (since Bavaria and Holland Malt belong to the same holding; Royal Swinkels). Table 13 presents the inputs that are necessary for 1 hl beer, based on a brewery with an annual production capacity of 400,000 hl (FAO, 2009). However, note that this data is relatively old and for most breweries, the raw input material per hl of beer is much lower currently.

Table 13. Raw material input needed to produce 1 hl of beer, based on an annual production capacity of 400.000 hl (FAO, 2009, pp. 29, table 11)

Input material	Value and unit per 1 hl beer
Malt	18 kg
Hops	0.15 kg
Yeast	0.6 litres
Water	7 hl

The input needed to produce 1 hl beer at the Dutch EU ETS breweries that are analysed in this report are shown in Table 14. Mainly due to the sheer size of the breweries, and therefore the associated economies of scale, and due to efficiency improvements in the last decade, some inputs needed to produce 1 hl of beer are lower than presented in Table 13.

Table 14. Raw material input needed (averages) for 1 hl beer; based on interviews with the EU ETS breweries

Input material	Value and unit per 1 hl beer
Malt	15 - 18 kg
Hops	0.15 kg
Yeast	0.6 litres
Water	3.8 hl

In Table 15, the prices per main material are given.

Table 15. Price of main raw materials

Products	Price (€/tonne)	Source	Comment
Malt (not roasted)	468	(Statista, 2020)	*See Table 3*
Hops	5,280 - 9,500	(European Commission, 2020b)	Average EU-27 price in 2019 of *bitter* hops
	6,760 – 9,590	(European Commission, 2020b)	Average EU-27 price in 2019 of *aroma* hops
Yeast	N/A		

2.4.2 Output

Beer

The total production volume in the Netherlands has been steady over the last decade and was roughly 25 million hl in 2016 of which 14 million hl has been exported (The Brewers of Europe, 2017). In the same year, about 12 million hl of beer has been sold in the Netherlands (of which 85% was brewed in the Netherlands) (Nederlandse Brouwers, n.d.). In 2017, the total production value was 2.5 billion euros, and with this value the Netherlands are the fifth beer producer of Europe (CBS, 2018b). The total export of beer in 2017 was valued at 1.7 billion euros.

As can be seen in Table 6, the Dutch EU ETS breweries export a large share of their production volume to foreign countries, with Heineken being the most export-orientated, Grolsch has the largest domestic share.

Table 16 Ratio between domestic and foreign export volumes for Dutch EU ETS breweries

Company	Ratio between domestic and foreign sales	Source
Heineken Netherlands Supply	27% domestic 73% export	(Kempers, 2018)
Grolsch	60% domestic 40% export	(Grolsch, n.d.)
Bavaria	35% domestic 65% export	(Royal Swinkels Family Brewers Holding N.V., 2020a)

In the last several years, there has been an increase in the sales of special beers and non-alcoholic beer (Nederlandse Brouwers, n.d.). The last category increased with 32.4% in 2018 compared with the year before and since 2010 it has quintupled. Special beers increased with 10.2 percent in 2018 compared with the year before. The four EU ETS breweries that are analysed in this report have a differentiated product portfolio ranging from pilsner to special beer (rosé beer, dark beers et cetera) to alcohol-free beer. Some of the sites produce only a few different products, whilst other breweries have a larger range of different products.

Spent grains

Spent grains are the residue of wort production in the brewhouse. It mainly consists of the insoluble covering layers of the barley malt (husk, pericarp and testa) (Wilhelmson, et al., 2009). According to Brewers' Guardian (2011) up to 30% of the weight off the initial malt grist is recovered after the brewing phase (dry weight) (Brewers' Guardian, 2011). Using the presented value of 15 – 18 kg of malt needed to produce 1 hl of beer (see Table 14), this amounts to 4.5 to 5.4 kg of spent grains per hl of beer. Traditionally this is either discarded, or sold as animal feed (Brewers' Guardian, 2011; Wilhelmson, et al., 2009).

Waste water

Not all the water that is used ends up in a bottle of beer. For example, a lot of water is used to clean the machines. This 'contaminated' water needs to be purified before it can be disposed. Therefore, all the breweries have their own wastewater treatment facility. Based on information from the breweries, the total amount of wastewater that is disposed is, averaged over all the breweries, around 0.27 m^3 per hectolitre of packed beer**.** Which is significantly lower than the value that is presented by the FAO; 0.55 m^3/hl for a 400,000 hl brewery (FAO, 2009). However, it is within the literature range of what is reported in the 2019 European Commission BREF document on the food, drink and milk industries: 0.25 – 0,60 m^3/hl (Giner Santonja, Karlis, Stubdrup, Brinkmann, & Roudier, 2019).

2.5 Mass and energy balance

In Figure 8 the average mass and energy balance of beer brewing in a Dutch EU ETS brewery is presented. This flow chart shows how much input of raw material and energy in general is needed in a Dutch EU ETS brewery to produce one hectolitre of beer. The energy input values are based on the figures presented in Table 11. The input and output flows of the raw materials are based on the figures presented in paragraph 2.4. Note that the assumption is made that natural gas is used to feed an on-site boiler or CHP that produces steam. In some cases, steam or hot water boilers are used additionally. Electricity can be either generated via the on-site CHP or is supplied by the external electricity grid.

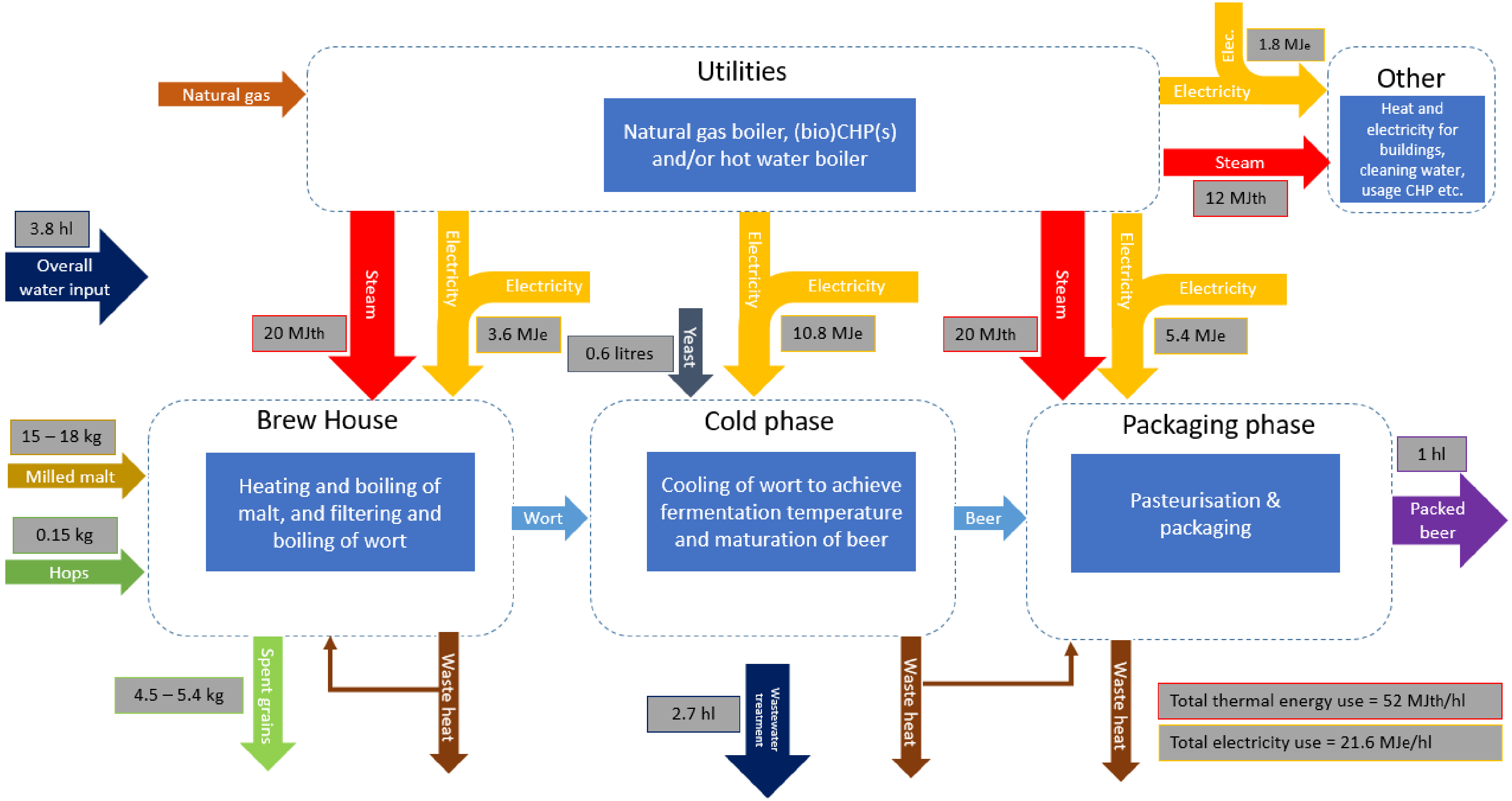

Figure 8. Mass and energy balance of beer production in Dutch EU ETS breweries.

** Note that fresh water is displayed separately on the left side of the figure for aesthetic reasons, since fresh water is used for more than one particular phase and the exact allocation is not known. However, most of the water is added in the brew house. Likewise, the wastewater treatment arrow is also not attached to a single phase for that same reason. Furthermore, note that electricity flow is displayed as a flow coming from an on-site CHP and is also displayed with an open end, meaning that electricity is generated from the CHP's on-site and imported from the external electricity grid, but the exact allocation is not known.*

3 Options for decarbonisation

In this chapter we identify and describe the most technically feasible and viable decarbonisation options that are applicable for maltings and breweries. These options can be derived from literature or are options that are put forward by the breweries and maltings themselves. Note that in this chapter, decarbonisation options that are possible for maltings could also be applicable for breweries and vice versa. This will be elaborated if this is the case.

3.1 Decarbonisation options energy-intensive industry

A variety of on-site decarbonisation options currently exist for the energy-intensive process industry. Overall, the following measures can be distinguished (Roelofsen, de Pree, Speelman, & Witteveen, 2017; VEMW, 2016):

1. efficiency improvements;
2. heat cascading (making use of waste heat);
3. electrification of heat demand;
4. green fuels[17];
5. change of feedstock (for example shift to biobased feedstock);
6. energy and/or heat storage to improve efficiency;
7. increasing reuse, remanufacturing and recycling;
8. carbon capture and storage/or utilisation (CCS/CCU).

According to Berenschot (2017), four pathways exist towards a sustainable heat supply for the Dutch industry: electrification, geothermal energy, bioenergy and fossil fuels combined with CCS/CCU (Berenschot, CE Delft, Industrial Energy Experts & Energy Matters, 2017). Figure 9 shows the decarbonisation options per industry, as established by Roelofsen et al. (Roelofsen, de Pree, Speelman, & Witteveen, 2017). The chart states that electrification of the heat demand and renewable energy for machine drive are the only viable decarbonisation solutions for the Dutch food, beverages and tobacco industry. Berenschot (2017) and Roelofsen et al. (2017) recognise the following new technologies that are applicable to the food, beverages and tobacco-industry: (1) electric boilers; (2) heat pumps (with a COP[18] of 2 – 3 or higher); (3) mechanical vapour recompression and steam recompression with a COP of 10. Furthermore, it is worthwhile for breweries to look into the possibilities of geothermal energy and the integration of hydrogen into a brewery's energy system.

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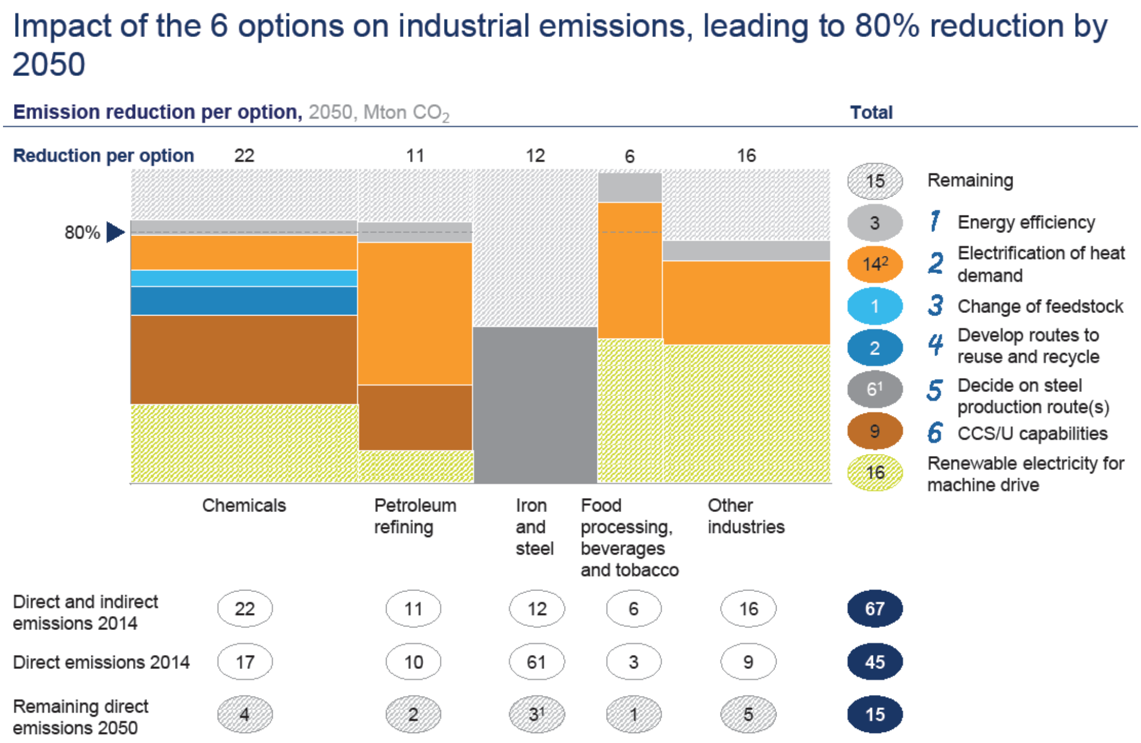
[17] Biogas is a green fuel, since it is part of the 'short' carbon cycle, the involved emissions have no long-term effect on the GHG equilibrium in the atmosphere, they are not considered in the carbon footprint, or the EU ETS. For more information: http://www.onlyzerocarbon.org/carbon_cycle.html

[18] The efficiency of a heat pump is expressed as the coefficient-of-performance (COP): the ratio of the heat delivered by the heat pump to the electricity input (Blok & Nieuwlaar, 2016).



NOTE: Assumed 50 EUR/MWh electricity, 24.4 EUR/MWh gas, 100 EUR/MWh hydrogen. Differences in totals due to rounding
1. Reduction of 6 Mton includes 3 Mton reduction from dedicated power plant. Hence remaining emissions include 3 Mton direct emissions and 3 Mton indirect emissions from steel. 2. This would assume 100% decarbonization of power supply to lead to 14 Mton emission reduction. When taking the indirect emissions into scope (of 22 Mton) it would correspond to decarbonization of power supply of 80% - in line with our previous report.
SOURCE: Centraal Bureau voor de Statistiek (2014), "Energiebalans" and "Energieverbruik" databases, National Inventory Report (1990-2014)

Figure 9. Impact of the 6 options on industrial emissions, leading to 80% emission reduction by 2050 (Roelofsen, de Pree, Speelman, & Witteveen, 2017, p. 31)

3.2 Energy efficiency improvements

Firstly, the possible energy efficiency measures are discussed since energy efficiency is usually the first step of decarbonisation. In this chapter the most viable energy efficiency measures with the highest potential are presented.

3.2.1 Maltings

A significant reduction of the heat consumption of a malt house in Denmark was related to the installation of a *glass tube heat exchanger* that recovers some of the vaporized energy of water from the 'air off' from the kiln to preheat the ambient air coming into the kiln (Danish Energy Agency, 2015; Carbon Trust, 2011a). Improvements in either horizontal or vertical systems are being researched and implemented (Royal Swinkels Family Breweries N.V., 2021). During the pre-break phase of kilning this glass tube heat exchanger is able to recover about 20% of the energy available in the „air off" stream.

Maltings are currently also looking at the implementation of heat pumps, not only to decrease CO_2 footprint (see 3.3.2), but to increase energy efficiency. Two recent examples can be found at *Intermalt* in Vietnam and *Global Malt (Tivoli Malz)* in Germany (Royal Swinkels Family Breweries N.V., 2021). The latter reported a reduction of its overall energy consumption in the kiln by 9%. The advantages for heat pumps in energy efficiency are that the exiting warm air from the kiln can be reused better to pre-heat the incoming cold air stream.

Another possibility to save energy is the improved process control via empirical AI-powered models (Royal Swinkels Family Breweries N.V., 2021). Energy efficiency is reached by the implementation of a mathematical model to schedule kiln drying in a double-deck kiln. The energy advantage can be gained by using the model prediction to time hot air reutilisation from the outgoing stream. These systems/models might still be much in their infancy, but potential is present for the future.

3.2.2 Breweries

The following decarbonisation options for breweries were found as energy efficiency improvements.

Efficiency improvements of wort boiling

Since a lot of thermal energy is used during wort boiling, it seems viable to look into techniques that can improve the thermal efficiency of wort boiling. Several measures are discussed.

Evaporation rates vary between 4- and 12% during the wort boiling phase (Carbon Trust, 2011b). Heat is consumed to evaporate the water in the wort vessel. This process could be optimised, consequently saving steam (and thus natural gas in the boiler room). An evaporation rate reduction of 1 percentage point can already lead to a reduction of 2 MJ/hl wort (Xhagolli & Marku, 2014). Therefore, measures that *lower the evaporation rate* can lower the heat consumption with only a small adjustment and low investment costs:

- A measure to lower the evaporation rate is *dynamic low pressure wort boiling*. Dynamic low pressure wort boiling uses an internal boiler and a vacuum pump to lower the pressure in the copper kettle. The process goes as follows: the wort is boiled for a short time (3 minutes, 100 °C), to remove any air from the vessel (Willaert & Baron, 2004). Consequently the vents are closed. Dynamic low pressure boiling then entails usually six phases of pressure building up (1.17 bar, 104 °C) and releasing (1.05 bar, 101 °C). The boiling is ended with a post-boiling phase (5 minutes, 100 °C) using circulating cooling water underneath the vessel to quickly drop the temperature of the wort. Small bubbles arise which strip the wort from volatiles. Dynamic low-pressure boiling reduces boiling time (to 45 min.), and has a lower evaporation rate (2.5 – 4 %) compared with conventional wort boiling (Willaert R. , 2007). Shortening the boiling time of wort will also decrease the thermal energy required and thus the amount of fossil fuels needed per hl of beer (Xhagolli & Marku, 2014).
- Another measure to reduce the evaporation rate is the utilisation of a *wort stripping column*. This measure comes with a modification to the wort boiling vessel. Wort is kept at boiling temperature in a conventional kettle, where no significant evaporation occurs, and nearly all the necessary processes occur such as hop extraction. However, the volatiles accumulate in the wort and are still present. Therefore, the wort is sent to a so-called ‘stripping column’ (Galitsky, Martin, Worrel, & Lehman, 2003). The wort moves down the column, while at the same time steam is injected, the steam flows up the column, condensates and leaves and thereby removing wort volatiles (see Figure 10). Evaporation can be kept under 2%, and boiling time is reduced to 40 min. The result is a reduction of thermal energy needed due to shorter boiling time, lower evaporation rates and lower boiling temperatures than in the conventional way of wort boiling. The stripped volatiles can even be collected or combusted, thereby preventing odour pollution that is associated with atmospheric brewing.

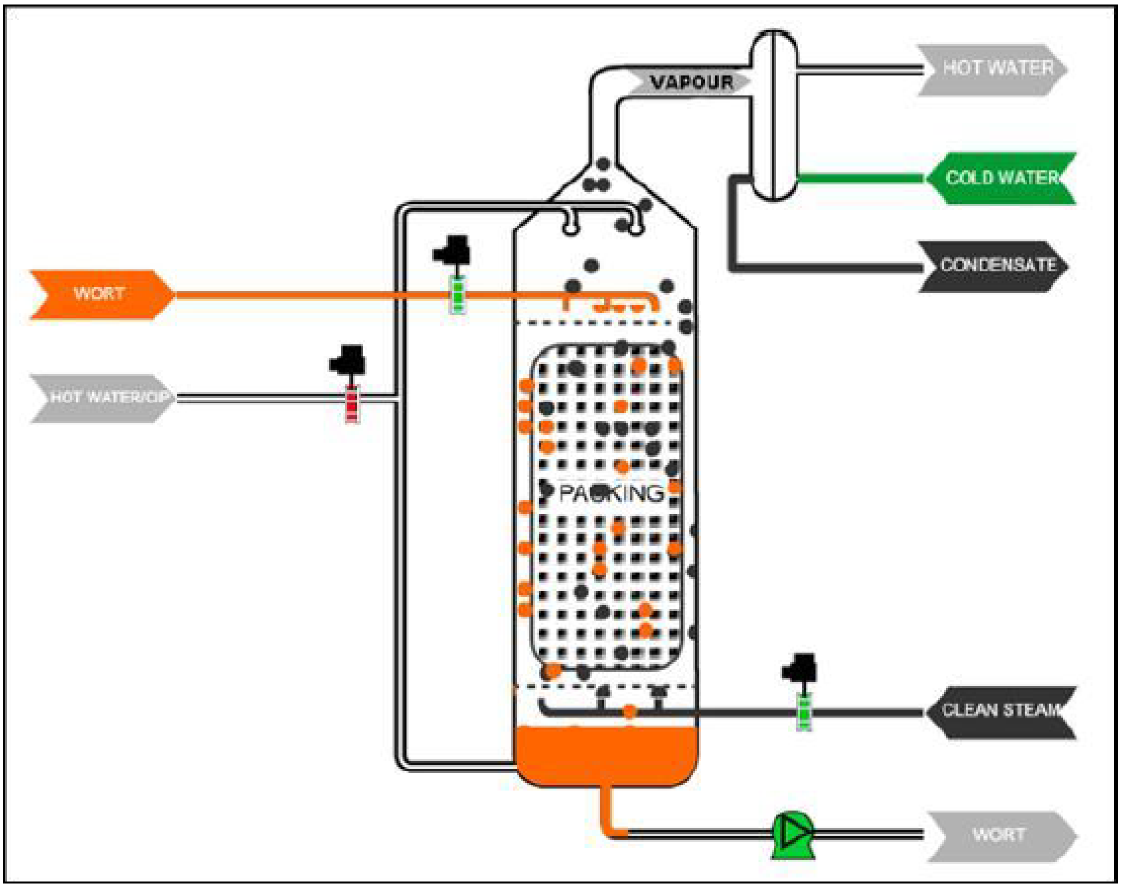


Figure 10 Schematic drawing of a wort stripping column. Source: (Carbon Trust, 2011b)

The wort boiling-phase normally involves an external heat exchanger (or calandria), where steam or hot water is used to externally heat the wort. The circulation of the fluid leads to a relatively even distribution of heat during the wort boiling-phase. An *internal boiler* is more efficient than external boilers due to a lower heating medium temperature, plus the wort spreader (part of the internal boiler) increases evaporation surface (thus the stripping of volatiles occurs more efficiently) (Scheller, Michel, & Funk, 2008) (Willaert & Baron, 2001).

Another method called *steam injection*, whereby steam is directly injected to the wort in the kettle, can lead to a reduction of thermal energy consumption (Carbon Trust, 2011b). Steam heats and mixes the liquid simultaneously and transfers energy more efficiently. Direct steam injection can, compared with an external boiler, save up to 40% in energy and 50% in cooking time (OAL Group, 2018).

Lastly, *raising the gravity*, or the concentration, of wort comes with some beneficial conditions. The same amount of beer can be made from a smaller amount of high-concentration wort. Fewer wort needs to be heated for the same amount of beer output, and this leads to an energy reduction. The beer will be brought to the correct alcohol-level in a later stage in the production process using deoxygenated water (Andrews, et al., 2011) (Sturm, Hugenschmidt, Joyce, Hofacker, & Roskilly, 2013) (Stewart, 2007).

Efficiency improvements for pasteurisation

Possible pasteurisation techniques can be used to lower that heat demand. *Flash pasteurisation* involves beer being heated for a short amount of time and being cooled in a heat exchanger prior to filling (Carbon Trust, 2011b) (Xhagolli & Marku, 2014).

(Conventional) tunnel pasteurisation involves already packed beer (cans or bottles) to be heated up to the desired temperature with hot water. As the glass of the bottles is also heated up to the desired temperature, thermal energy is wasted by heating packaging material. Flash pasteurisation can therefore lead to a thermal energy reduction.

Another option is *UV pasteurisation*. UV pasteurisation involves a UV-light source which can reduce the number of microbes in the beer. Energy needed to neutralise microbes using UV-light is dramatically lower than that of thermal (conventional) tunnel pasteurisation (Carbon Trust, 2011b).

Continuous brewing

All the efficiency measures previously mentioned focused on brewing as a batch-process. Continuous brewing is the opposite of batch brewing and wort is continuously produced and processed. Continuous brewing, or more specifically, continuous wort boiling, entails boiling at higher temperatures (of 130 °C or 140 °C) for a short period of time (3 – 5 minutes) (Willaert & Baron, 2004). The higher boiling temperature accelerates the chemical processes. An evaporation rate of around 7% is required to remove volatiles. Continuous wort boiling allows the steam demand of the brewhouse to be maintained at a constant level, thereby preventing peak demands that are present in the batch-process of wort boiling. However, continuous wort boiling is difficult to manage with several different worts (O'Rourke, 2002). The most important reason to switch to continuous brewing: it reduces the peak consumption of utilities, since the processes happens continuously and cooling and heating is better integrated. The *Martens* brewery in Belgium (3 million hectolitres/year) was the first large brewery to commercially adopt continuous brewing in 2006[19]. Electricity and steam consumption are halved and no more peak loads occur.

3.3 Decarbonisation of heat demand

All the aforementioned energy efficiency measures are aiming to reduce the thermal energy needed per hectolitre beer produced. However, they are incremental and their potential is limited. If natural gas remains the fuel for steam production these measures can contribute to improve efficiency, but will not lead to the vast emission reduction that is needed to reach zero on-site emissions in 2050. Therefore, in this section, options for the decarbonisation of the heat demand are described.

3.3.1 Electrical boiler

Electrification of the heat demand in the form of electrical boilers is in many industries the main important decarbonisation measure. No information was found during the literature review on the application of electrical boilers in large breweries, although it was mentioned by literature addressing the food, beverage- and tobacco industry. There are two main types of electrical steam boilers that are used at industrial scale in this sector: the electrode boiler and the resistance element boiler (Berenschot, CE Delft, Industrial Energy Experts & Energy Matters, 2017). The electrode boilers are available with capacities of up to 70 MW_e and can produce saturated steam with temperatures up to 350 °C and 70 bar. Electric boilers with resistance elements instead of electrodes can heat up air or other gasses to 600°C. However, the capacity of an electrical resistance boiler are typically much smaller with a max of 5 MW_e. Since the processing temperatures of malt and beer production does not exceed 170 °C and higher capacities than 5 MW_e are required, the *electrode* boiler is more suitable for the maltings and breweries. The CAPEX and OPEX of electrode boilers are shown in Table 17. It

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[19] https://www.meura.com/documents/casestudy/nl10themeurabrew.pdf, accessed on 01-05-2020

should be stated that the electrode boiler only counts as a decarbonisation option when the electricity is produced by a renewable energy source directly or it could be proved, by means of Guarantees of Origin for example, that renewable energy is used.

Table 17. Characteristics of electrode boilers.

Characteristics	Value	Reference
Fuel input	Electricity	
Energy output	Steam (up to 350 °C and 70 bar)	(Berenschot, Energy Matters, CE Delft, & Industrial Energy Experts, 2017)
Emissions	0 tCO_2 (if green electricity is used)	
Input capacity	20 MW_e	(Marsidi & Lensink, 2020a)
Output capacity	19.8 MW_{th}	(Marsidi & Lensink, 2020a)
Efficiency	99%	(Marsidi & Lensink, 2020a)
Full load hours	2000 h/yr*	(Marsidi & Lensink, 2020a)
TRL	9	(Berenschot, Energy Matters, CE Delft, & Industrial Energy Experts, 2017)
Technical lifetime	15+ yr**	(Marsidi & Lensink, 2020a)
Investment cost	115 €/kW_{th}	(Marsidi & Lensink, 2020a)
Operational cost	49 €/kW_{th}/yr Fixed operational costs 0.037 €/kWh_{th} Variable operational costs	(Marsidi & Lensink, 2020a)

* In theory full load hours could be higher. In 2030 a fully renewable electricity supply can be probably guaranteed for 8000 hr/y.
** The reported economical lifetime is 12 year, but the technical lifetime is generally longer.

3.3.2 Waste heat recovery

Vapour recovery methods

The vapours that are vaporised during the wort boiling are often still blown off from the brewhouse into the atmosphere, without recovering latent heat (up to 6.67 MJ/hl). The latent heat still present in these vapours could be recaptured via different vapour recovery techniques (Sturm, Hugenschmidt, Joyce, Hofacker, & Roskilly, 2013; Xhagolli & Marku, 2014).

Mechanical vapour (re)compression (MVR) can be applied to recompress the vapours. The compressor extracts and compresses wort vapours to an overpressure of 0.3 or 0.4 bar (Willaert & Baron, 2004). These vapours can be mixed with steam and used to heat the boiler.

Another technique to recover the latent heat in the exhaust vapours and reduce energy costs in evaporation, is via *thermal vapour compression*. In this process, steam from a boiler with an overpressure of at least 8 bar is fed to a steam pump, after which the water vapour is sucked in and compressed to a small overpressure (0.1 – 0.4 bar), and can consequently be used to (pre-)heat the wort via an heat exchanger (Sorrell, et al., 2000). This form of vapour (re)compression, as well as the MVR technology, is mainly used for atmospheric boiling since higher evaporation rates are necessary to advocate an investment (Willaert & Baron, 2004). Investments are typically not viable for boil-offs below 4% (Carbon Trust, 2011b).

A third technique is *vapour condensation*, where considerable amounts of heat can be saved using a vapour condenser in combination with an energy storage system (Sorrell, et al., 2000). Vapour condensation cannot be used in combination with mechanical vapour recompression, but it could be combined with thermal vapour recompression. In this case, both systems get a portion of the vapours from the kettle (Galitsky, Martin, Worrel, & Lehman, 2003).

Which of the three mentioned vapour recovery methods should be used, depends on the evaporation rates, the hot water demand and the costs for thermal and electrical energy (Willaert & Baron, 2004). The CAPEX and OPEX of a reference *mechanical vapour recompression* heat pump are shown in Table 18. It could be assumed that these figures are also applicable for the other two vapour recovery methods; *thermal vapour compression* and *vapour condensation.*

Table 18. Characteristics of a reference mechanical vapour recompression heat pump MVR (Marsidi & Lensink, 2020b).

Characteristics	Value
Fuel	Steam, waste heat (2.5 barg, 138 °C)
Energy output	Steam (10 barg, 184 °C)
Emissions	0 tCO_2 (if green electricity is used)
Capacity	5 MW_{th}
Full load hours	8000 h/yr
Electricity use	714 kW_e
Efficiency (COP)	7
Technical lifetime	12+ yr*
TRL	7-9**
Investment cost	1602 €/kW_{th}
Operational cost	18 €/kW_{th}/yr Fixed operational costs 0.008 €/kWh_{th}/yr Variable operational costs

* The reported *economical* lifetime is 12 year, but the *technical* lifetime is generally longer.

** Although not literally stated in the source, this is in accordance with the general principle that technologies in the SDE should be innovative but reliable.

Furthermore*, energy storage systems* can be used to store thermal energy during wort boiling and wort cooling, leading to a potential energy reduction[20] and thus less carbon emissions (Sturm, Hugenschmidt, Joyce, Hofacker, & Roskilly, 2013). Considerable amounts of thermal energy can be conserved using for example a vapour condenser in combination with an energy storage system and using the stored energy for wort (pre)heating (Willaert & Baron, 2004).

Heat pumps

Heat pumps can be used to recover thermal energy from refrigeration system condensers which mostly blow low grade waste heat (around 30 °C) into the air in conventional refrigeration systems (Carbon Trust, 2011b; Olajire, 2012). Likewise, the heat that arises during the anaerobic digestion in the wastewater treatment system can be captured with heat exchangers. Mostly, this effluent heat is used to heat up the influent to improve the efficiency of the internal circulation reactor (anaerobic digester). However, this low temperature waste heat (also around 30 °C) could also be used as a source for a heat pump.

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[20] See also: https://www.gea.com/en/products/ess-energy-storage-system.jsp

This heat could potentially be used to heat water up to around 80 °C, which can be used for instance for pasteurisation and bottle washing. Potentially, a COP of around 5 could be reached by using two heat pump systems (with ammonia or butane as a refrigerant for the heat pump for example) and the average payback time could be less than three years (Carbon Trust, 2011b). Since a heat pump uses electricity and not natural gas, scope-1 carbon emissions can be abated if green electricity is used. The CAPEX, OPEX and other characteristics of a reference industrial compression (closed system) heat pump are shown in Table 19.

Table 19. Characteristics of a reference industrial compression (closed system) heat pump. Source (Marsidi & Lensink, 2020b)

Characteristics	Value
Fuel	Waste heat (30 °C)
Energy output	Hot water (80 °C)
Emissions	0 tCO_2 (if green electricity is used)
Capacity	2000 kW_{th} output
Full load hours	8000 h/yr
Electricity use	571 kW_e input
Efficiency (COP)	3.5
Technical lifetime	12+ yr*
TRL	7-9**
Investment cost	1140 €/kW_{th}
Operational cost	26 €/kW_{th}/yr Fixed operational costs 0.015 €/kWh_{th}/yr Variable operational costs

* The reported *economical* lifetime is 12 year, but the *technical* lifetime is generally longer.

** Although not literally stated in the source, this is in accordance with the general principle that technologies in the SDE should be innovative but reliable.

3.3.3 Energy system changes

Oil heat system

Several (modern) breweries around the world (like in the United Kingdom and the United States[21]) changed from a water/steam system to a thermal fluid system, using thermal fluids instead of steam for their thermal processes in the brewhouse. Such a thermal fluid heating system is unpressurised and therefore cheaper to operate and maintain compared to steam networks. These heat systems could lead therefore to more efficient thermal energy use around the brewery, leading to lower carbon emissions. However, large investment costs (in the order of 100 thousand to million euros) are necessary to change the infrastructure on-site of breweries or maltings. It is therefore more likely that only new to-be-built breweries would invest is such a heating system.

Hydrogen combustion

Potentially, hydrogen can serve as an energy carrier at breweries. Hydrogen could be used as an alternative for natural gas to be fed in the on-site boiler for the production of electricity or steam. For hydrogen to be regarded a decarbonisation alternative however, it should be produced from renewable resources. Hydrogen is categorized to three categories based on its production route; ‘grey’, ‘blue’ and ‘green’ hydrogen. Grey hydrogen involves the production of hydrogen from fossil-fuels with CO_2 emissions resulting from the production process. Most of the hydrogen currently on the market is grey hydrogen produced by steam methane

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[21] https://www.foodbev.com/news/brewer-cuts-energy-cost-savings-of-80-with-new-thermal-fluidheater/ and https://www.brewersjournal.info/rebellion-beer-company-completes-thermal-fluid-installation/, accessed on 01-05-2020

reforming (SMR). Blue hydrogen is also produced from fossil fuels, however the CO_2 emissions during production are captured and stored underground or utilised for other purposes. Lastly, green hydrogen is produced using renewable resources. Currently, the most employed technology for the production of green hydrogen is electrolysis of water using green electricity. The economic feasibility of using hydrogen depends largely on its production route, the available infrastructure for hydrogen and the price of hydrogen which currently is higher than the price of natural gas (de Bruyn, Jongsma, Kampman, Gorlach, & Thie, 2020).

To convert a conventional boiler to a hydrogen boiler, only some adaptations need to be made to the boiler's burner (VNP, 2018). This could have an impact on the boiler's capacity, reducing it perhaps by 10%. The characteristics of a hydrogen boiler can be found in Table 20 together with the investment and maintenance costs.

Table 20. Characteristics of hydrogen boilers

Characteristics	Value	Source
Fuel	Hydrogen	
Energy output	Steam	
Emissions	Water vapour, NOx	(E4tech, UCL Energy Institute, & Kiwa, 2015)
Capacity	Same as on-site gas boiler of 5 – 200 MW_{th}	(E4tech, UCL Energy Institute, & Kiwa, 2015)
Efficiency	100% (HHV) 85% (LHV)	(VNP, 2018)
Technical lifetime	15-25 years	(VNP, 2018)
TRL	9	(E4tech, UCL Energy Institute, & Kiwa, 2015)
Investment cost*	98.3 GBP_{2015}/kW (121.11 $€_{2020}$/kW**)	(E4tech, UCL Energy Institute, & Kiwa, 2015)
Operational cost	3.2 GBP_{2015}/kW/yr Fixed operational costs (3.94 $€_{2020}$/kW/yr **)	(E4tech, UCL Energy Institute, & Kiwa, 2015)

* *These are the average investment cost to convert the conventional gas boiler to a hydrogen boiler.*

** *Conversion from GBP_{2015} to EUR_{2020}: GBP_{2015} to GBP_{2020} 11.59% inflation*[22] *and 1 GBP_{2020} = 1.104 EUR_{2020}*[23].

Hydrogen can also be used as a fuel in a conventional gas-turbine CHP installations to generate steam and electricity. Though the technology has an estimated TRL of 7-9 its application to large scale industry is limited (SBC Energy Institute, 2014). The 16 MW Fusina plant in Italy is the first industrial-scale application featuring a hydrogen fuelled gas turbine and heat recovery steam generator (Power Engineering International, 2010). Table 21 shows the costs of installing a new hydrogen-fuelled CHP plant. To save money and maximize the lifespan of existing installations, research into retrofitting natural gas CHPs to hydrogen or flexibly fuelled CHPs is ongoing. In Hamburg a natural gas CHP is being converted to hydrogen and the Dutch Topsector Energie is also involved in a project regarding retrofitting CHPs to hydrogen (Ali, 2019; Topsector Energie, n.d.).

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[22] Source: https://www.in2013dollars.com/uk/inflation/2015

[23] Exchange rate on December 8th 2020: https://nl.exchangerates.org.uk/historische/GBP-EUR.html

Table 21. Characteristics of a hydrogen CHP.

Characteristics	Value	Reference
Fuel input	Hydrogen	
Energy output	Steam, electricity	
Emissions	Water vapour, NO_x	
Capacity	1 – 300 MW_e	(SBC Energy Institute, 2014)
Electrical efficiency (HHV)	< 45% open cycle < 60% combined cycle	(SBC Energy Institute, 2014)
Technical lifetime	20 years	(E4tech, UCL Energy Institute, & Kiwa, 2015); (SBC Energy Institute, 2014)
TRL	7-9	(SBC Energy Institute, 2014)
Investment cost	389 - 555 GBP_{2015}/kW (480 – 685 $€_{2020}$/kW*)	(E4tech, UCL Energy Institute, & Kiwa, 2015)
Operational cost	0.003 - 0.0043 GBP_{2015}/kW/yr Fixed operational costs (0.004 – 0.005 $€_{2020}$/kW/yr*)	(E4tech, UCL Energy Institute, & Kiwa, 2015)

** Conversion from GBP_{2015} to EUR_{2020}: GBP_{2015} to GBP_{2020} 11.59% inflation[22] and 1 GBP_{2020} = 1.104 EUR_{2020}[23].*

Hydrogen production

Switching from natural gas to hydrogen requires a stable supply of carbon-free hydrogen. This could be imported via trucks, ships or via a to be built hydrogen piping network. The price of grey hydrogen is currently around 1.50 €/kg and largely determined by the price of natural gas (van Hulst, 2019). Future blue hydrogen will be priced higher than grey hydrogen, with its price being driven by the price of natural gas as well as the cost of carbon capture and storage or reuse. The price of blue hydrogen is expected to quickly come down after the deployment phase, when CCS/U is scaled up and standardized. The price of green hydrogen is currently between 3.50-5 €/kg as a result of the limited capacity for electrolysis and costs of green electricity (van Hulst, 2019). At current prices, using green hydrogen is economically not viable. However, if current CO_2 pricing trajectories continue, the price of hydrogen derived from natural gas will increase (van Hulst, 2019). At a CO_2 price of 30 €/tonne blue hydrogen becomes cheaper than grey, and at a price of 60 €/tonne CO_2 green hydrogen becomes competitive (GasTerra, 2019). Add to this the technical developments leading to a decreasing price of electrolysers and of renewable electricity, and green hydrogen becomes a viable, sustainable alternative (van Hulst, 2019).

3.3.4 Bio based options

Biomass or biogas can be used instead of natural gas for the production of steam, hot water and/or electricity to achieve CO_2 reduction. Breweries and maltings can use different means that are available on-site to realise this.

Culms and spent grains as a biofuel

Culms and spent grains, which are left over after de-culming in maltings or after the wort production phase in breweries, can be applied as a bio-based fuel. Generating energy with the combustion of culms or spent grains instead of selling it as animal feed, which is the status quo currently, provides an interesting alternative use of this 'waste' product. Culms or spent grains can be used as an energy source in two ways (Wilhelmson, et al., 2009; Mussatto, Dragone, & Roberto, 2006):

1. drying and **direct combustion** to generate electricity and/or heat;

2. the production of biogas (a mixture of 60-70% methane, carbon dioxide and small proportions of hydrogen, nitrogen and carbon monoxide) or natural gas quality gas via **anaerobic digestion.**

Direct combustion

The need for drying before combustion depends on the moisture content of the culms or the spent grains. Culms or spent grains with a moisture content of 35 – 40% can usually be combusted directly and dewatering- and combustion technology is widely available to achieve this (Wilhelmson, et al., 2009; Scheller, Michel, & Funk, 2008). Culms and spent grains have an energetic value of approximately 17.4 MJ/kg (LHV) for dry weight and 1.3 MJ/kg (LHV[24]) for wet weight (Koppejan, Elbersen, Meeusen, & Bindraban, 2009). The technology to burn spent grains and recover the energy (heat and/or power) has been available for several years now and is already in operation at several breweries (Brewers' Guardian, 2011). Brewers' Guardian (2011) states that:

"One vision of the future would see breweries becoming 'biorefineries' with emphasis placed not solely on beer production but on maximising the useful energy and/or co-products that can be generated from the raw material feedstocks entering the site." – (Brewers' Guardian, 2011, p. 62).

In most cases, the current boilers on the site could be easily replaced by direct-fired biomass boilers. In Table 22 the characteristics of a reference direct-fired biomass boiler are presented.

Table 22. Characteristics of a reference direct-fired biomass boiler (Cremers, Strengers, Beurskens, & Lensink, 2020).

Characteristics	Value
Fuel input	Culms or spent grains
Energy content of fuel	17.4 GJ/tonne dry weight 1.3 GJ/tonne wet weight
Energy output	Steam
Emissions	0*
Capacity	20 MWth
Full load hours	8500 h/yr
Efficiency	90%
Technical lifetime	12+ years**
TRL	7-9***
Investment cost	605 €/kW$_{th}$
Operational cost	46 €/kW$_{th}$/yr Fixed operational costs 0.004 €/kWh Variable operational costs

* In reality, CO_2 is emitted when biomass like spent grains are burned. However, emissions from the burning of biomass are allocated to the point where the biomass is produced and harvested. Next to this, the spent grains are a rest product that are produced either way in the production process of maltings or breweries. Hence, the emissions from the use of biomass by the breweries or maltings are considered to be zero.

** The reported *economical* lifetime is 12 year, but the *technical* lifetime is generally longer.

*** Although not literally stated in the source, this is in accordance with the general principle that technologies in the SDE should be innovative but reliable.

Since the four Dutch EU ETS breweries are responsible for 90 – 95% of total Dutch annual beer production, they are also responsible for 90 – 95% of the beer sector's spent grains output. Approximately 500,000 tonnes of spent (beer) grains (wet, 78% moisture content) are available in the Netherlands annually (TNO, 2013). This means at minimum (90% *

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[24] LHV = Lower Heating Value

500,000 tonnes) 450,000 tonnes of spent grains for the Dutch EU ETS breweries. Considering a wet weight energetic value of 1.3 MJ/kg (LHV) and a boiler efficiency of 80%[25] (for biomass burners that use co-products), a theoretical potential of approximately 468 TJ of saturated steam from spent grains combustion can be available for all the EU ETS breweries.

It is debatable however, in a holistic sense, whether culms or spent grains should be used as fuel instead of feedstock for animals, since cattle feed already has such an impact on the Earth's resources and an alternative for cattle feed consequently needs to be found. Furthermore, culms and spent grains are currently a large source of income for the maltings and breweries. Regardless, for the Dutch EU ETS maltings and breweries, culms and spent grains can be an important and viable biomass-fuel that can contribute to deep decarbonization.

Anaerobic digestion

Another option is to digest the culms or spent grains by microorganisms to convert it to biogas. The produced biogas (CH_4 + CO_2) could be upgraded to natural gas quality and could then be burned in the original gas boiler or CHP to generate heat and/or electricity. Furthermore, biogas can also be produced on site by the anaerobic digestion of the brewery's wastewater (Scheller, Michel, & Funk, 2008). Table 23 lists the characteristics and the costs for three different reference options: anaerobic digestion installation to produce high-quality renewable biogas, an anaerobic digestion installation that produces heat and electricity, and an anaerobic digestion installation where the gas is immediately burned in a boiler to produce heat.

Table 23. Characteristics of reference anaerobic digestion installations (Boots, Wolbers, & Lensink, 2020).

Characteristic	Digester, renewable gas	Digester, CHP	Digester, heat
Fuel input	Culms or spent grains	Culms or spent grains	Culms or spent grains
Fuel reference input capacity	5.5 MW input	5.5 MW input	5.5 MW input
Output	Renewable biogas	Heat and electricity	Heat
Emissions	0*	0*	0*
Full-load hours	8000 hr/yr	8000 hr/yr electricity 7300 hr/yr heat	7000 hr/yr heat
Internal heat demand	5% of produced biogas	5% of produced biogas	5% of produced biogas
Electric output capacity		2.3 MW_e	
Thermal output capacity		2.6 MW_{th}	4.7 MW_{th}
Maximum efficiencies		41% electrical efficiency 47% assumed thermal efficiency	85% assumed thermal efficiency

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[25] (Carbon Trust, 2011a)

Characteristic	Digester, renewable gas	Digester, CHP	Digester, heat
Investment cost	880 €/kW input for digester 404 €/kW output for gas upgrading	898 €/kW input	879 €/kW$_{th}$ output
Fixed operational costs	111 €/kW input	81 €/kW input	44 €/kW$_{th}$ output
Energy content substrate	3.4 GJ biogas/tonne	3.4 GJ biogas/tonne	3.4 GJ biogas/tonne
Technical lifetime	12 years**	12 years**	12 years**
TRL	7-9***	7-9***	7-9***

* In reality, CO_2 is emitted when biomass like spent grains are burned. However, emissions from the burning of biomass are allocated to the point where the biomass is produced and harvested. Next to this, the spent grains are a rest product that are produced either way in the production process of maltings or breweries. Hence, the emissions from the use of biomass by the breweries or maltings are considered to be zero.

** The reported *economical* lifetime is 12 year, but the *technical* lifetime is generally longer.

*** Although not literally stated in the source, this is in accordance with the general principle that technologies in the SDE should be innovative but reliable.

3.3.5 External residual heat

Large industries or waste incineration plants could have large amounts of residual heat which can be utilized. It is estimated that in the Netherlands approximately 100 PJ of waste heat per year could be used usefully (CE Delft, 2019). Residual heat becomes available in a variety of processes and activities. The heat that is not used is mostly discharged into the surface water or to the air via flue gases or evaporation via cooling towers. However, this residual heat could be used for heating homes, greenhouse horticulture or other industrial processes with a heat demand. When residual heat is captured efficiently, it could be supplied to these several different end users, either via a direct pipeline from the heat producer (with a heat source) to an end user (or users) or via a distribution network or heat network (indirect supply). When breweries or maltings are in the vicinity of an industry that has residual heat, this waste heat can potentially be used for their activities. In Figure 11 an overview is given of potential waste heat sources in the Netherlands. Vice versa, residual heat from the breweries could in turn provide heat to other industrial companies, horticulture or residential areas. By providing waste heat to heat networks, the amount of free European Emission Allowances allocated to the breweries and maltings by the NEa could be increased.

Note however that the usefulness of the waste heat is dependent on the temperature and volume of the waste stream. It could be possible for instance that another industry only can supply heat of maximum 70-80 °C hot water and is not able to deliver steam. In such a situation, additional heat pumps are needed to achieve the desired temperature level.

A common issue that often arise with residual heat is the question whether the heat is actually ‘green’, since waste heat mostly has its origins in the combustion of fossil fuels. Next to this, it is a risk for companies to commit to a waste heat source since it cannot be certain in advance whether the heat source will also be in operation in the future. A large part of the capital investment (around 80%) usually goes to installation of pipelines between a residual heat source and an off taker (Muller & Lensink, 2020). The purchase and installation costs of an underground pipeline lie between approximately 1,000 and 3,000 euro per metre, but this greatly depends on the location.

Table 24 shows the costs for a reference waste heat project, where waste heat is extracted from an industry and transported to a waste heat network, horticulture or any other off taker.

The investment cost listed includes a 10 km long pipeline from an industry plant to a heat consumer.

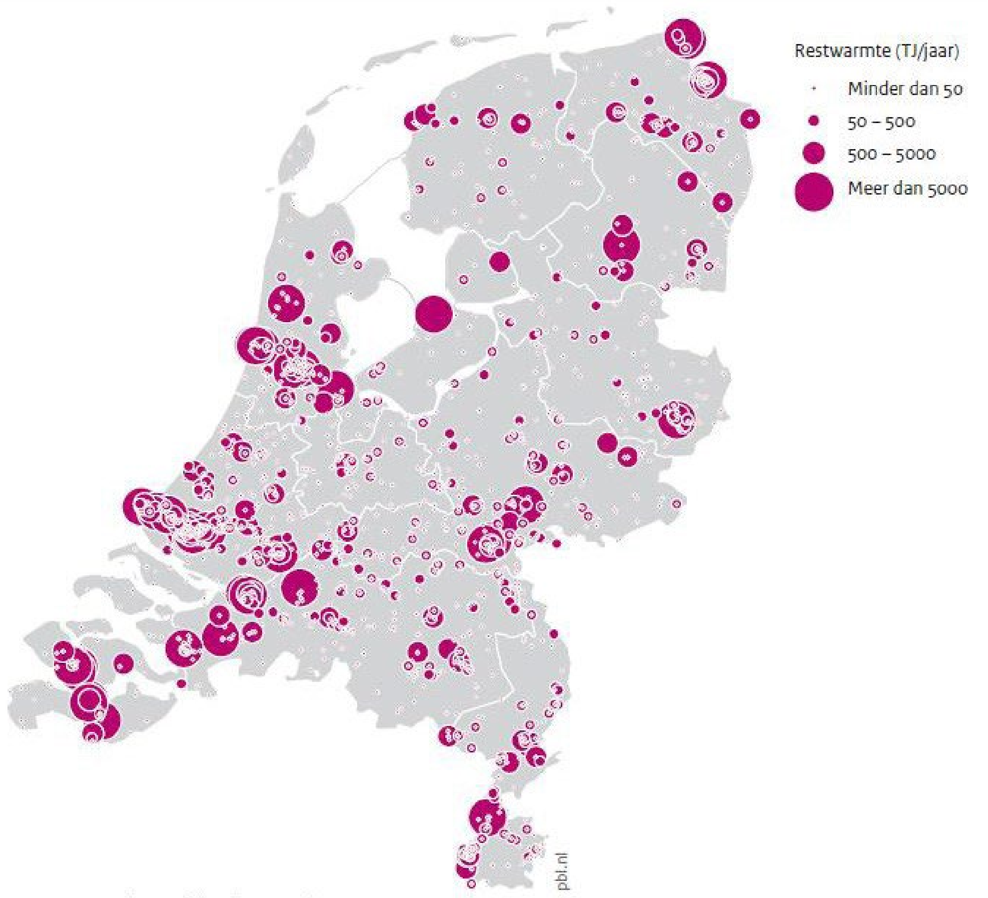

Figure 11. Overview of the licensed discharges of heat in the Dutch national waters. The large dots on the map are mostly large power plants and the energy intensive industries. Source: (CE Delft, 2019)

Table 24: Characteristics of a reference waste heat project from industry to a consumer (assuming a 10 km pipeline) *(Muller & Lensink, 2020)*.

Characteristics	Value
Main output	Waste heat/water (70-80 °C)
Output capacity	10 MW_{th}
Full load hours	6000 h/yr
Emissions	0 tCO_2*
Electricity use	0.018 kWh_e/kWh_{th} output**
Technical lifetime	15+ years***
TRL	9
Investment cost	1411 €/kW_{th}
Operational cost	29 €/kW_{th}/yr Fixed operational costs 0.001 €/kWh Variable operational costs

* In reality, CO_2 is emitted in the industrial processes that precede the waste heat production. However, these emissions could be counted zero when this left-over heat would otherwise be wasted to the environment.

** Electricity is used in transportation pumps and heat exchangers. When green electricity is used, the emissions are assumed to be 0.

*** The reported *economical* lifetime is 15 year, but the *technical* lifetime is generally longer (up to 30 years).

3.3.6 Ultra-deep geothermal energy

Ultra-deep geothermal energy is another technique that could be used for the production of steam in the malting and brewery sector. With this technology heat (in the form of hot brine water) is extracted from a heat reservoir deep underground and converted to steam above ground via a heat exchanger. After the exchange, the cooled pressurised brine will subsequently flow back deep into the ground, repeating the cycle. Geothermal energy is considered ultra-deep when below 4000 meters depth. With this depth, temperatures of 120 – 140°C are expected to be reached which can thus be useful for heating purposes in the malting and brewery sector (IRENA, 2019; in 't Groen, Tolsma, Mijnlieff, & Smekens, 2020). Note however that a geothermal source needs to be in close proximity of the brewery or malting since transporting high temperature heat over long distances is mostly too costly. Next to this, geothermal heat is probably not the most suitable source for breweries and maltings, since they mostly operate in a batch process, while geothermal heat needs a continues off-taker of the heat.

The costs and lifetime specification for ultra-deep geothermal energy are shown in Table 25.

Table 25. Characteristics of geothermal energy. Source (in 't Groen, Tolsma, Mijnlieff, & Smekens, 2020)

Characteristics	Value
Input	Geothermal energy (heat)
Main output	Steam
Emissions	0 tCO_2
Capacity	17 MW_{th}
Full load hours	7000 h/yr
Electricity use	5490 MWh/yr
Technical lifetime	15+ yr*
TRL	9
Investment cost	2509 €/kW_{th}
Operational costs	107 €/kW_{th}/yr Fixed operational costs 0.008 €/kWh_{th} Variable operational costs

* The reported *economical* lifetime is 15 year, but the *technical* lifetime is generally longer (up to 30 years).

3.3.7 Other options

Next to the aforementioned options to replace natural gas, there are theoretically more options that could be considered. Renewables like solar-PV and wind energy can possibly make the electricity use 'greener'. Next to this, solar thermal energy collectors, like flat-plate collectors and parabolic throughs can generate renewable heat (Scheller, Michel, & Funk, 2008). However, it is not likely that these techniques will bring about large on-site CO_2 mitigation since these techniques cannot provide heat or electricity on demand and also require a substantial amount of space.

Next to this, carbon capture utilisation and storage (CC(U)S) is a theoretical option to reduce the on-site CO_2 emissions. This could mean that investments need to be made to capture CO_2 and transport it to a CO_2 backbone. The most promising CO_2 backbone for CCS that is currently in the developing phase is the Porthos pipeline in Rotterdam which will transport CO_2 to the North Sea for storage in the subsurface of the North Sea. Since most maltings and breweries are relatively far from this backbone, large investments (millions of euros) are needed to transport captured CO_2. Therefore, CCS does not seem a viable option for maltings and breweries since the CO_2 emissions of the maltings and breweries are relatively too low for such a costly decarbonisation option.

4 Discussion

This chapter describes which decarbonisation options the maltings and breweries already undertake and which future decarbonisation plans they have to meet their own or the latest Dutch climate goals. Subsequently, this chapter explores which decarbonisation options, mentioned in the previous chapter, are applicable to and are most viable for the maltings and breweries.

4.1 Current activities and future decarbonisation plans

It is important to bear in mind that the maltings and breweries not always choose the best energy efficiency or decarbonisation method for beer quality reasons or in order to maintain the special character of the beer (for example changing boiling temperatures or duration). Even so, most of the Dutch EU ETS breweries are already aiming for the next, disruptive step needed for deep decarbonization. All six sites approach the decarbonisation transition in a unique and surroundings-involving matter.

4.1.1 Heineken Zoeterwoude

Formerly, Heineken Zoeterwoude aimed to be part of a district heat network called 'Leiding over Oost' that should have connected the industries in the harbour of Rotterdam with Leiden, Oegstgeest and the greenhouse horticulture in the Zuidplaspolder (Shell, n.d.). This network could have potentially supplied 80% of the heat demand in Zoeterwoude (Kempers, 2017). In the original plans, Heineken Zoeterwoude planned to cover the remaining 20% of the heat demand with on-site generated biogas (10%), external biogas (5%) and some small heat demand-reductions (5%). However it has been decided in 2020, due to financial reasons, to discontinue the 'Leiding over Oost' project entirely (Energeia, 2020a). Nevertheless, Heineken might connect to a future heating network called *Warmtelinq* that still is under development. It is planned that this network connects the Rotterdam harbour with Delft and the Hague, and the heat suppliers hope to reach their customers in Leiden (and therefore more in the vicinity of Heineken Zoeterwoude) via this route after all. This heat network should be operational in 2026 or 2027.

Another option for Heineken Zoeterwoude is the production of more biogas, that can be used to generate steam. Currently, Heineken Zoeterwoude already creates biogas from its own wastewater treatment (via anaerobic digestion), which is used to produce around 8% of the total steam usage (Groene Cirkels, n.d.). Heineken is currently cooperating with the green recycling company Wagro to investigate the possibilities to process leaf juice from tomato and pepper leaves in Heineken's wastewater treatment system to produce biogas. This biogas could be used to produce heat for Heineken or for the horticulture in the vicinity of Zoeterwoude (Kempers, 2018).

As stated in the previous chapter, spent grains as a biofuel could also be used to cover a substantial part of the brewery's thermal energy demand. The following estimate was made based on the literature review. Spent grains allocated to production volume gives the following share for Zoeterwoude: 175,500 tonnes[26] (wet weight). Furthermore, spent grains have an energetic value of 1.3 MJ/kg for wet weight (moisture content 78%) (see also

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[26] $10.4\ million\ hectolitres\ (output\ volume\ Zoeterwoude)/\ 26.8\ million\ hectolitres\ (total\ volume\ Dutch\ EU\ ETS\ breweries$ in 2017) = 39%. 39%*450,000 tonnes spent grains (see paragraph 3.3.4) = 175,500 tonnes Wellicht aanpassen met nieuwe productievolumes?

paragraph 3.3.4), which means a potential total energy value of approximately 228.15 TJ. When assuming a boiler with an efficiency of 80%[27] for biomass burners that use co-products at least (80% * 228.15 TJ =) 182.52 TJ of saturated steam could be generated by the combustion of spent grains alone. This means a steam production of approximately 18 MJ/hl, which means that, considering Table 11 (the calculation of Anton Wemmers), this could almost cover the thermal energy demand of the brewhouse.

Another way in which Heineken wants to improve their heat integration is by extracting heat that is formed during fermentation. At Heineken Zoeterwoude they are currently working on an innovative demonstration project in which residual heat is extracted from the fermentation process and upgraded to a higher temperature level by means of a heat pump (Topsector Energie, 2019). This heat could in turn be used in their primary production processes. Heineken applied for DEI+[28] subsidy for this project and they were granted a subsidy amount of 2.8 million euros.

A substantial part of the electricity demand (40%) is currently covered by the wind turbines of wind farm Barrepolder, which are located in the vicinity of the brewery and are owned by Heineken (Kempers, 2017). In the future, Heineken aims to first lower their electricity demand by means of electricity savings. The remaining demand is supposed to be covered by other wind farms and other renewable technologies like tidal and solar energy.

4.1.2 Heineken Den Bosch

Although Den Bosch is an older brewery than Zoeterwoude, still most of the decarbonisation methods focused on breweries that were found during the literature research are already incorporated: low(er) evaporation rates, shorter boiling periods, high gravity brewing, energy storage systems, heat exchangers and flash pasteurisation. Continuous brewing is not relevant for the brewery in Den Bosch.

Currently, 8% of the total gas demand is covered by the generation of biogas from their own wastewater treatment plant. Furthermore, Heineken Den Bosch currently offtakes approximately 5 million m^3 biogas per year from the wastewater treatment plant of the *Aa en Maas* water authority (Waterschap Aa en Maas, 2018; RVO, n.d.). This saves up to 7,000 tons of CO_2 per year.

Upscaling the biogas consumption is a realistic possibility, and could possibly reduce the on-site emissions to nearly zero. Since the infrastructure is already in place, the only requirement is the availability of the biogas from the Aa en Maas water authority. In the near future, at least half of the heat demand of the brewery will be covered by this biogas (Het Parool, 2018).

In 2013, Heineken Den Bosch installed more than 3600 solar PV panels, a capacity of approximately 900 kWp, on the roofs of the buildings at the brewery (RVO, 2015). Which could, at that time, potentially cover the electricity demand of one of their products. Since 2019, Heineken expanded their solar-PV capacity at the Den Bosch site to 16,569 panels in total, which made the brewery number 1 on the list of breweries with installed PV-systems on their own site (Duurzaam ondernemen.nl, 2019). According to the managing-director of Heineken Den Bosch, the total installed PV-systems have produced enough green electricity to fill about 20 million bottles of beer in three months.

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[27] (Carbon Trust, 2011a)

[28] *Demonstratie Energie- en Klimaatinnovatie*. A Dutch subsidy scheme for demonstration projects.

Next to this, the brewery offtakes electricity from a wind turbine in the vicinity, with a capacity of 2.3 MW, and there are plans to ‘connect’ three more wind turbines in 2021 (Duurzaam ondernemen.nl, 2019).

Another decarbonisation option for Heineken Den Bosch is capturing the residual heat from fermentation (as explained in paragraph 3.3.2). The amount of heat at fermenting is directly linked to total beer production. Potentially, half of the thermal energy demand could be covered by using the residual heat from fermenting in combination with heat pumps, a hot water-system and electricity. The most important requirement is a new system that uses hot water to transport heat and heat pumps to lift the heat to the desired temperature.

4.1.3 Grolsch

Currently, Grolsch uses biogas that is generated via their own wastewater treatment plant to cover 22% of the thermal energy demand (Grolsch, 2018). Grolsch also already incorporated the vast majority of decarbonisation methods focused on breweries that were found during the literature research: reduced wort boiling-periods, low(er) evaporation rates, high gravity brewing, internal boilers, wort stripping columns, vapour recompression, energy storage systems and heat recovery systems. Since 2019, the brewery installed a heat integration system in which waste heat that becomes available during wort boiling is captured to pre-heat a next wort boiling batch. According to Grolsch, this measures realised a 1.5% energy reduction.

Grolsch mentions that continuous wort boiling is not a relevant decarbonisation option considering the many different product types they produce. The added value of continuous brewing; the heat integration and therefore reduced thermal energy demand, is lost during the cleaning, and heating of the system in between different product types.

Grolsch has the ambition to become CO_2 neutral brewery by 2025. The Grolsch brewery aims at replacing the natural gas-fired boiler house with steam derived from a biomass fuelled[29] incineration system, which is located at the waste processor in the vicinity of Grolsch called *Twence,* in 2022 (Twence, n.d.). Grolsch could receive steam via a to-be-realized direct pipeline. Via this route, Grolsch estimates that 72% of the yearly gas demand could be reduced which would lead to a reduction of 5,500 tonne CO_2 per year.

Furthermore, Grolsch is currently exploring Power to Heat (P2H) in the form of a hot water-system in combination with heat pumps (Grolsch, 2018). Fairly large investments (several million euros) are necessary, since large parts of the water-network need to be revised or even newly built. Possibly, the capacity of the electricity infrastructure also needs to be expanded. Moreover, Grolsch also considers electric boilers but since the electricity infrastructure already needs to be expanded for heat pumps, this will require an even larger expansion. An important requirement is thus that the infrastructure can cope with the increased electricity demand.

4.1.4 Bavaria/Holland Malt Lieshout

The Bavaria brewery already implemented some energy efficiency measures during the last several years. They use an internal boiler, with subsequently wort stripping columns. Furthermore, Bavaria uses ± 1 million m^3 of biogas that is generated from their own wastewater treatment plant. This biogas is used in two on-site gas motor CHP’s, which were installed in 2005, which produce 5,800 MWh of heat and 4,400 MWh of electricity annually

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[29] From non-renewable waste wood that originates from the construction industry.

(Agentschap NL, 2010). This self-generated biogas corresponds to roughly 3% of the gas demand.

Furthermore, Bavaria invested in 2015 in a heat pump of 1 million euro that uses residual heat from the cooling process of the brewery to be used in the kilning process of the malting unit[30]. Additionally, Bavaria installed 1,280 on-site solar PV panels on their distribution centre in 2017. More recently, Bavaria applied for SDE+ subsidy in 2020 for the installation of a large PV solar rooftop project (Energeia, 2020b). It concerns approximately 15 square hectares and they applied for a capacity of 15 MW which they hope will produce 14.7 GWh of electricity per year. Furthermore, Bavaria is used as a test site by the TU Eindhoven to investigate the application of iron powder as a source to store energy by means of electrolysis.

Next to this, a glass tube heat exchanger is installed at both locations Lieshout and Holland Malt (Van Iersel, 2018). This, in combination with a new hot water buffer (2020), lowers the need for hot water from a natural gas boiler. Part of the steam net is now therefore replaced by a warm water piping system (95 °C). With these new systems, and with the new frequency controlled equipment that is also installed, the malting and brewery at the Lieshout-site are much better coordinated (Royal Swinkels Family Breweries N.V., 2021).

Subsequently, water saving systems have been implemented in the last couple of years, which significantly reduced the need for fresh water (Royal Swinkels Family Breweries N.V., 2021).

For the longer term, Bavaria/Holland Malt Lieshout is focusing on the use of geothermal energy. Together with other parties, they are investigating potential areas where drilling in Oost-Brabant can take place[31]. According to www.thermogis.nl, the technical potential for geothermal energy at this location would be more than 10 MW_{th}. More than fifty locations are being investigated so that potentially the whole region, companies as well as residential areas, could use geothermal energy to cover a large part of the heat demand. Bavaria wants to offtake steam at 140 degrees Celsius. They can cascade condensate that they do not need to other off-takers in the area. The steam can be used either for their heating processes, but also to drive a generator to generate electricity. Estimated on-site costs are approximately €25 million until 2025.

4.1.5 Holland Malt Eemshaven

Holland Malt Eemshaven is planning to become the largest and the most sustainable malting in the world[32]. They want to be completely natural gas-free and aim to be completely CO_2-neutral in the future. The malting is focussing on the potential of using residual heat from neighbouring industrial sites and power plants such as Nuon Magnum (natural gas), Eems units (natural gas) and RWE Eemshaven (coal) (within a 4 km range)[33]. However, all these power plants use fossil fuels so for this to become a really sustainable heat option, these power plants should either use biomass instead of fossil fuels or use CC(U)S. Furthermore,

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[30] https://automatie-pma.com/automatie/beurs-en-brancheberichten/bavaria-bespaart-energie-door-warmtepomp/, accessed on 01-06-2020

[31] https://www.ed.nl/laarbeek/bavaria-brouwt-vanaf-2020-enlsquo-aardwarmtepilsenrsquo-br~adbed3bd/, accessed on 01-06-2020

[32] Groninger Ondernemers Courant. “Moutfabriek Eemshaven moet grootste ter wereld worden”. 2018. Retrieved from https://www.groningerondernemerscourant.nl/nieuws/moutfabriek-eemshaven-moet-grootste-ter-wereld-worden. Accessed on 17-01-2020.

[33] Investerings- en Ontwikkelingsmaatschappij voor Noord-Nederland. “NOM kijkt om: Pak ergens in de wereld een biertje en drink een beetje trots uit de Eemshaven”. 2019. Retrieved from https://www.nom.nl/nommer-artikelen/nom-kijkt-om-pak-ergens-in-de-wereld-een-biertje-en-drink-een-beetje-trots-uit-de-eemshaven/. Accessed on 17-01-2020.

the coal power plant will shut down before 2030 and the current status of the negotiations on a heat exchange network in the Groningen harbour is not clear.

Next to this, the malting looks into the electrification of their heat demand and into the use of geothermal energy as a heat source.

Furthermore, Holland Malt Eemshaven has a potentially favourable position with regard to the North Sea, e.g. for CCS or access to offshore wind energy. No official plans for connection however are known currently.

4.2 Concluding remarks

When addressing the current production processes of the Dutch EU ETS maltings and breweries a few general statements can be made. The two Dutch maltings have a specific energy consumption that is on a benchmark level and mostly more energy efficient than many other maltings in the world. The four breweries are already more efficient than could be derived and/or expected from the different scientific and professional reports devoted to the production of beer. Furthermore, the decarbonisation options (found as energy efficiency improvements in the literature) are mostly already in place, or deemed not relevant. Additionally, energy improvements established via continuous brewing are not considered by the breweries for a variety of reasons: either the differentiated product-portfolio cancels out the involved energy reductions or the SEC of the site is already comparable to the SEC typical for continuous brewing, so large investments do not make any sense.

The main focus for decarbonisation in maltings and breweries is therefore on the replacement of natural gas for heat and electricity. Electric boilers are currently and on the short run, not seen as interesting decarbonisation option by the breweries and maltings; on-site infrastructure and the capacity of the electricity grid can currently not handle the highly increased electricity demand involved with electric boilers, and current energy prices (that is, low gas prices and relatively high electricity prices) make it not a realistic, viable solution for profit-seeking maltings and breweries. Another possible option, vapour recompression, can only lead to minor energy reductions, due to the low evaporation rates at the four brewery locations. Heat pumps, in combination with renewable electricity, are the only measure found in the general literature that is considered by the breweries to be an important technology that can contribute to zero on-site emissions in 2050 (or even 2030), but technology must become ready. Heat pumps can be mainly used to recover on-site waste heat from for example the cooling towers needed for the fermentation stage.

(Green) hydrogen as a fuel to generate heat and/or electricity is not deemed to be a viable cost-effective decarbonisation options. Especially not for the short-term. Green hydrogen is not yet widely available and the investment and operational costs too import hydrogen are currently too high. Electrolysers or fuel cells on-site are not yet fully developed and also still too costly to purchase or to operate. In fact, even when hydrogen becomes more available in the regions where the maltings and breweries operate, it seems more logical that other industries that need hydrogen as a feedstock should have priority over its use prior to industries that use hydrogen for the generation of relatively low grade (lower than 200 °C) heat.

Replacing natural gas by biogas/biomass is a potentially good decarbonisation measure for most breweries and maltings. Recovering biogas via anaerobic digestion from the on-site wastewater treatments could already replace large amounts of natural gas and only requires minor changes/investments to the current boilers. Next to this, using spent grains as a biomass source could potentially cover a large part, if not completely, of the thermal energy demand of the breweries. However, this option is currently not considered by most breweries due to the revenues they make by selling it as animal feed.

The Dutch EU ETS maltings and breweries also look for other methods to drastically lower their emissions, since relatively well-known emerging technologies not always form a suitable and/or financially viable alternative for on-site decarbonisation. Maltings and breweries are therefore currently mainly looking for external heat-sources, like geothermal energy or external residual heat, or external biofuel-sources in the region in close vicinity to the sites. This means they will be collaborating more with other regional organisations and firms in the future. Breweries should therefore meticulously consider the consequences of their decarbonisation choices. Depending on third-party resources might not prove to be optimal in the future, as on-site decarbonisation choices are then highly influenced by off-site developments.

An internal factor that hampers the transition towards zero on-site emissions in 2050 (or 2030) is that the maltings and breweries are in a lock-in situation due to path-dependency. All the breweries still use steam as heat medium in the brewhouse and this could limit future decarbonisation options. This lock-in was previously of less importance with incremental measures, as those often lead to energy and cost reductions.

Regulatory factors also heavily influence the transition trajectory of Dutch EU ETS breweries. Uncertainty regarding the future is present in terms of what has priority and which measures will be favoured by future policies. Whether the government will tax CO_2 emissions and subsidise decarbonisation measures impacts the decarbonisation transition.

The decarbonisation transition is thus still surrounded by uncertainties. One thing is certain: the heat demand at breweries will remain, since the production of malt and beer involves drying, heating, boiling and pasteurisation. The large investments involved with the options to decarbonise heat generation make the Dutch EU ETS maltings and breweries somewhat cautious, so they are also exploring other different decarbonisation options. Since most maltings and breweries aim to become climate neutral before 2030, investment decisions need to be made as soon as possible since new production systems have long depreciation periods and investment moments occur rarely (turn-arounds mostly occur once every 8 year). Windows of opportunity for decarbonisation are therefore scarce and decisions made now can affect the company for decades. Therefore, the maltings and breweries would be greatly assisted when Dutch policy on, for instance, SDE++ subsidy or the national carbon tax or other policies next to the EU ETS system are clearly communicated and clarified on a short notice.

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