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DECARBONISATION OPTIONS FOR THE DUTCH CERAMIC INDUSTRY

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MIDDEN

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Decarbonisation options for the Dutch ceramic industry

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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 EnergieTransitie. 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:
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TNO EnergieTransitie 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.

This report was reviewed by the Royal Dutch Association For Building Ceramics (KNB), the members of KNB, and independent knowledge and support centre of the Dutch ceramics technical industry (TCKI). PBL and TNO remain responsible for the content. The production volumes and capacity have not been verified by the companies. The specific energy and material consumption results are based on European data and may therefore deviate from the energy and material consumption of the Dutch ceramic industry. These specific consumption values should therefore be treated as indicative values.

Contents

FINDINGS

Summary

The Dutch ceramic industry can be distinguished in four main types of products: bricks, roof tiles, floor & wall tiles and refractory products[1]. At present, 43 ceramic plants are operational and covered by the Dutch ceramic association (KNB), many of them are located alongside the major rivers in the eastern and southern part of the Netherlands. Their total annual production capacity is estimated to be approximately 3.4 million tonnes end product, and brick and roof tile plants are responsible for 85% of the production. These products are being used as durable building materials with a long technical lifetime and made of renewable raw materials that are locally available.

The manufacturing process of ceramic products has five main steps:

- Preparation: Mixing the raw material (e.g. clay, loam) with water and additives.
- Shaping: Shaping the material to the required dimensions by moulding, pressing or extruding.
- Drying: Lowering the water content of the shaped green ware to less than 1%.
- Firing: Heating the dried product so that the required chemical reactions occur.
- Subsequent treatment: Additional decoration, packaging for transport.

The manufacturing process uses electricity and heat, supplied by the electricity grid and natural gas grid respectively.

CO_2 emissions can be related to two types of emissions during the manufacturing process, namely fuel emissions and process emissions. Fuel emissions result from the burning of natural gas and process emissions result from the calcination process of the ceramic material when it is heated to certain temperatures. The process emissions are on average 26% of total emissions, and the total specific CO_2 emissions of a ceramic product ranges from 0.18 to 0.48 tCO_2 per tonne end product.

Different decarbonisation options are identified for the Dutch ceramic sector, which can be distinguished according to the abatement categories of MIDDEN.

- Fuel substitution
  - Green gas: from the grid or from on-site gasification or digestion of biomass.
  - Hydrogen: hydrogen from the grid, burned by specific hydrogen burners.
  - Electric kiln and drying: using electricity – additional research is needed.
  - Microwave kiln and drying: using microwave radiation – additional research is needed.
- Use of residual energy
  - Heat exchange: Extracting energy (heat) from flue gases for drying.
  - Heat pumps: Closed heat pump system to reuse low temperature waste heat.
  - Hybrid drying: Drying in two steps: aerothermal and semi-steam drying.
- Process design
  - Ultra-deep geothermal: Extracting heat from layers below 4000m.

[1] Sometimes the ceramic industry is divided into 'coarse' (bricks, roof tiles) and 'fine' (wall, floor tiles, refractory products) ceramics. Both are part of this report.

    - Extended tunnel kiln: More efficient firing, but no residual heat available for drying.

- CO_2 capture and storage (or utilisation)
    - Post-combustion CCS: Capture of CO_2 from stacks followed by compression, or liquefaction, and storage.
- Product design
    - Lighter products.

There are options available that could technically decarbonise the drying process in the short term. Technologies to decarbonise the high temperature firing process, however, are still in an early development phase (electric kiln and microwave supported technology) and require further research. To reduce the CO_2 process emissions, only CCS can be applied. In addition, the following aspects should be considered in the decision process of implementing decarbonisation options: long lifetime of equipment (especially the firing kiln), relatively remote location of plants with possible grid capacity problems, and the interaction between decarbonisation options for the drying and firing processes.

FULL RESULTS

Introduction

This report describes the current situation for ceramic production 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 MIDDEN project will update and elaborate further on options in the future, in cooperation with the Dutch ceramics industry.

The ceramic industry produces solid materials comprising an inorganic compound of metal or metalloid and non-metal with ionic or covalent bonds. This study focuses on the production of ceramic products used in the construction or industry sectors, such as bricks, roofing tiles, wall- and floor tiles, and refractory products.

Scope

In the Netherlands, production locations covered include:

- 37 ceramic plants that have a minimum production of 75 t per day, thus reported under the EU Emissions Trading System (EU ETS). Many plants are located next to large rivers in the eastern and southern parts of the Netherlands. Six further plants (next to the 37) are not covered in the report since they are smaller than 75 t per day (see Section 1.2).

Production processes include:

- Preparation of material, shaping, drying, firing and subsequent treatment.

Products include:

- Facing bricks, paving bricks, inner wall bricks, roof tiles, wall and floor tiles and refractory products.

The main options for decarbonisation are:

- Fuel switching using green gas (either from the grid or produced on-site using gasification or digestion), hydrogen (from the grid), microwave assisted heating and drying or electric kilns and electric dryers, heat exchange from flue gases, heat pumps, ultra-deep geothermal, and CCS.

Reading guide

Section 1 introduces the Dutch ceramic industry. Section 2 describes the current situation for ceramic production processes in the Netherlands. Section 3 describes the main products of these processes, and options for decarbonisation are systematically quantified and evaluated in Section 4. The feasibility of and requirements for those decarbonisation options are discussed in Section 5.

1 Ceramic production in the Netherlands

This section provides a general overview of the ceramic industry in the Netherlands. The scope is limited to 37 ceramic plants that produce products used by the construction or industry sectors. The majority (29) of the plants produce bricks (i.e. facing bricks, paving bricks and inner wall bricks), five plants produce roof tiles, two plants produce wall and floor tiles and one plant produces refractory products.

The following sections describe the history of ceramic production in the Netherlands, visualize the production locations of these companies (Figure 3) and elaborates on each company's history, production locations, employees and revenues. Finally, Table 2 provides an overview of the calculated production volumes per location and EU ETS registered CO_2 emissions for 2016.

1.1 History of ceramic production in the Netherlands

The ceramic industry has a long history in the Netherlands due to the large rivers (e.g. the Rhine and Meuse) that transport sediments from the higher parts of Europe. The raw material (clay) sticks together in so-called embanked floodplains along the rivers, where it can be easily extracted and transported to, often, nearby situated ceramic plants (see Figure 1). Clay is considered a renewable raw material, because it is continuously brought to the Netherlands by the large rivers and ultimately, has to be taken out of the river basin as a means of high water security.

Figure 1. A typical location of a ceramic plant alongside the river. Source: (KNB, 2020).

This geographic advantage and rising local demand of ceramic products (mainly building bricks) resulted in the development of many manufacturing sites alongside the rivers with a peak of 900 plants at the second half of the 19^{th} century (see Figure 2). The decennia following this peak, plants were closed or merged due to a decreasing demand and increased global competition (Lintsen, 1993, p. 271).

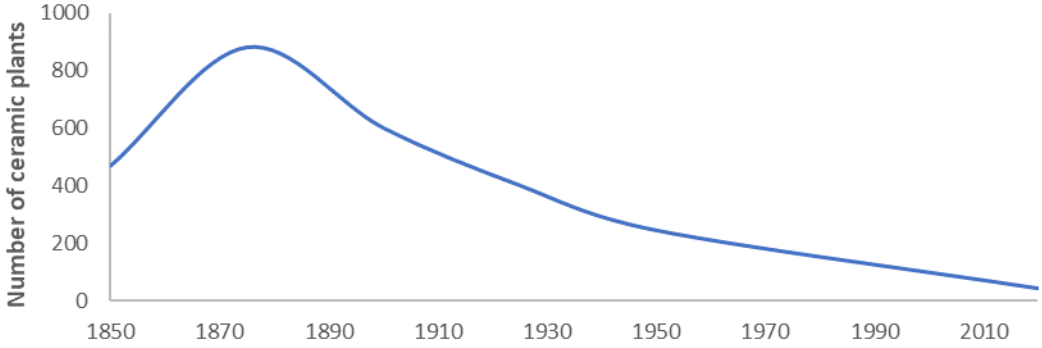


Figure 2. The rise and decline of the number of ceramic plants in the Netherlands over the last two centuries. Source: adapted from Corten (Corten, 1994), with the present number of plants included.

Today, there are 43 'coarse'[2] ceramic plants, owned by 16 companies, represented by the Dutch ceramic branch association (KNB) (KNB, 2020). The location alongside the river means that some of these factories are also located next or close to protected Natura2000 areas[3], which were clay extraction sites in the past, but are now restored nature areas. Nowadays, these Natura2000 areas have to be protected against nitrogen oxide depositions from factories, as for example ceramic production plants. This may result in conflicting interests with regards to decarbonisation options and the energy transition, when (the implementation of) CO_2 reduction measures may lead to additional nitrogen oxide emissions.

1.2 Ceramic production companies in the Netherlands

This report covers 37 production plants of which 36 are owned by companies represented by the KNB (see Figure 3 for their locations on a map). Six plants (out of the 43 plants that are represented by the KNB) are not included due to their relatively small production volumes (less than 75 t per day)[4]. Although these plants are not included, the described production process and decarbonisation options in Sections 2 and 4, also apply to them.

DEKO BV is excluded, despite being a member of the KNB. Reason for this is that DEKO is not a brick or tile manufacturer but produces relatively thin strips of bricks by sawing manufactured bricks (named in Dutch: 'steenzagerij').

Furthermore, Steenfabriek de Nijverheid and Steenfabriek de Volharding are considered one entity in this report because both are registered at the same address (and in the EU ETS list). The name of this entity is Steenfabriek de Nijverheid.

[2] Coarse ceramics are here defined as ceramics used in the construction sector.
[3] These are more than 150 special natura conservation areas in the Netherlands, designated according to the Habitats Directive and Birds Directive of the European Union.
[4] The not included plants are St. Joris Keramische Industrie BV, De Porceleyne Fles BV, Koninklijke Tichelaar Makkum, Steenbakkerij Zilverschoon Randwijk, Steenfabriek Vogelensangh, and Wienerberger Panningen.

The plant not represented by the KNB but included in this report (and part of the EU ETS) is Gouda Refractories B.V., manufacturer of refractory products. This plant is not represented by the KNB because it is not a manufacturer of building ceramics. Its products are meant for the inner lining of ovens for high temperature processes, such as in the glass or steel industry.

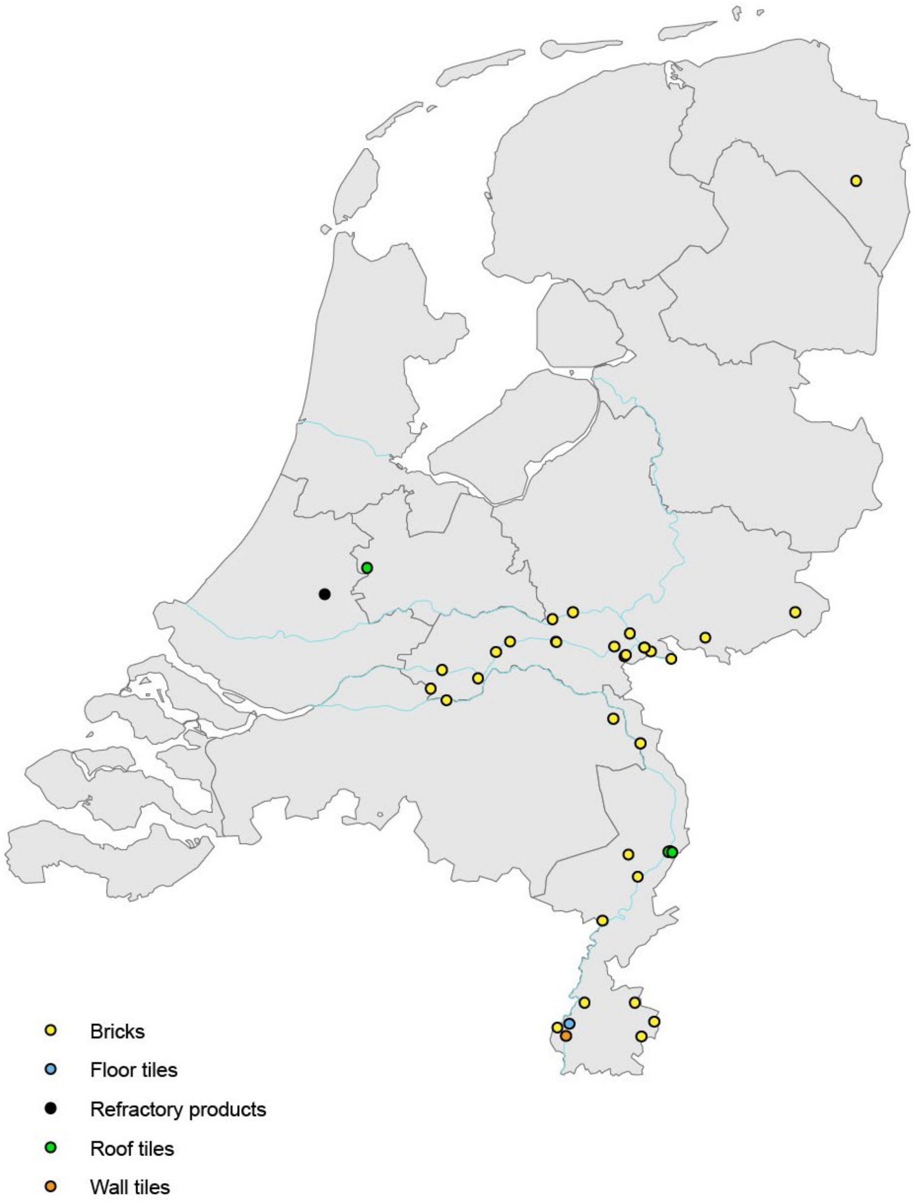


Figure 3. Map with the locations of the ceramic plants included in this MIDDEN report. Many of the plants are located alongside a big river.

1.2.1 Monier B.V.

Monier B.V. is part of the BMI Group, a leading manufacturer of roofing and waterproofing systems that is active in more than 40 countries. The BMI Group originates from 2017, when Braas Monier Building Group (founded in 1941) was acquired by Standard Industries. Around this time, Braas Monier Building Group employed 8000 people and owned 121 production facilities (Icopal, 2017). Within the Benelux, the brand name 'Monier' is used. Two plants of Monier B.V. are included in this report: Pannenfabriek Woerden and Pannenfabriek Tegelen. Both plants are manufacturers of roof tiles. The number of employees of Monier B.V. in the Benelux is approximately 180, including two concrete roof tile manufacturing locations and the head office (Monier B.V., 2020). The annual report of BMI Group shows that in 2016 the net revenues in the Netherlands were 46.9 million Euros (BMI Group, 2017).

Pannenfabriek Woerden has 18 kilns fired by natural gas and 24 drying chambers. The plant runs 24 hours per day continuously except for a few weeks during summer for maintenance work. It has an annual production capacity of 12 million roof tiles (Vos, 2018). The history of the plant goes back to 1793, when family Van der Kas acquired a roof tile bakery named 'Damlust'. Through the years it has changed ownership many times (and was rebuilt after being destroyed by fire in 1954) until it became part of Braas Monier Building Group in 2008 (Stichting Historie Grofkeramiek, 2020).

The plant in Tegelen has a similar production process (extruding roof tiles) and capacity as Woerden. The plant started manufacturing roof tiles in 1835 (Bouwtotaal, 2019).

1.2.2 Caprice Holding B.V.

Originally named HUWA, the company was renamed to Caprice Holding B.V. when the joint venture HUWA-Vandersanden unbundled in 2010, as a result of predictions that less houses would be built due to the financial crisis (Cobouw, 2010). Before unbundling, HUWA-Vandersanden owned three plants: Steenfabriek Huissenswaard, Spijk and Hedikhuizen. After unbundling, HUWA-Vandersanden kept Steenfabriek Spijk and Hedikhuizen. Caprice Holding B.V. became the owner of Steenfabriek Huissenswaard (Caprice Holding B.V., 2020).

Steenfabriek Huissenswaard is located in Angeren. The first activity of brick manufacturing dates to 1825, when F.C. Cock built the first ceramic plant. Steenfabriek Huissenswaard was the second plant built in Angeren and was founded by Derk Terwindt in 1837. Until 1978, the plant was owned by the Terwindt family. Over the years the plant underwent many transformations to increase its production, e.g. replacing its field kiln to a reverberatory kiln in 1928. In 1968 the plant started manufacturing facing bricks in addition to paving bricks. By 2004, another renovation led to the modernization of the shaping and drying process (10 drying chambers with each a capacity of 54 thousand bricks). Moreover, a new tunnel kiln was built, 145 meters long and with 14 rows with each row containing 25 gas burners (Wingas, 2020). The shaping of bricks is applied by a 'De Boer vormbandpers' that can be set to mould or press bricks in the defined dimensions (Caprice Holding B.V., 2020). Currently, Steenfabriek Huissenswaard has an annual production capacity of 75 million bricks (Caprice Holding B.V., 2020).

1.2.3 Engels Baksteen

In 1913, Leopold H.H. Engels received a permit to produce bricks in a plant named 'De Huishoek' located in Panningen. This was the start of the company Engels Baksteen that has remained within the family Engels to this day. The plant in Panningen was for more than 90 years the only production location of Engels Baksteen, until 2004 when the company acquired a plant located in Oeffelt. Since then, the plant in Panningen was named Steenfabriek Helden and the plant in Oeffelt was named Steenfabriek Oeffelt. Both plants are manufacturers of bricks: facing bricks in Steenfabriek Engels Helden B.V. and facing bricks & paving bricks in Steenfabriek Engels Oeffelt B.V. (baksteen.nl, 2017). The total number of employees is 40 and the two plants together have an annual production capacity of 130 million bricks WF (Engels Baksteen, 2020).

Steenfabriek Helden has been owned by Engels Baksteen since the beginning (1913). Through the years the plant has undergone many modifications, e.g. adding electricity (instead of steam) and mechanical pressing, but the most important change was the tunnel kiln which was installed in 1965. This tunnel kiln was replaced by a more modern and larger tunnel kiln in 1985, which is still operational. In 1997 a second tunnel kiln was built to double the production capacity (baksteen.nl, 2017, pp. 8, 9). Currently, the production capacity is 70 million bricks WF per year (Engels Baksteen, 2020).

The first sign of brick manufacturing at the current production site of Steenfabriek Oeffelt dates to 1844. At that time, Steenbakkerij Willem Graat was located here (Stichting Historie Grofkeramiek, 2020). In 1889 the location was taken over and named Steenfabriek Het Kruispunt. It was renamed to Steenfabriek Hagens when the family Hagens became owner of the plant. The plant stayed within the family until 2004, when it was acquired by Engels Baksteen. Currently, the plant produces bricks using moulding and pressing techniques (baksteen.nl, 2017, p. 9). The annual production capacity is 60 million bricks WF (Engels Baksteen, 2020).

1.2.4 Euro-Steenhandel B.V.

Euro-Steenhandel B.V. is a family business founded by Hubert Linssen in 1907 (Stichting Historie Grofkeramiek, 2020). The company has owned one plant since the beginning: Steenfabriek Linssen, located in Kerkrade. Currently, this plant has a production capacity of approx. 15 million bricks WF per year and the total number of employees is 20 (Euro-Steenhandel B.V., 2020). The company is specialized in mechanical moulding. It has placed solar panels on the plant’s roof in 2015 (Euro-Steenhandel B.V., 2020).

1.2.5 Steenfabriek Klinkers B.V.

Steenfabriek Klinkers B.V. is a family business that has existed since 1938. Their ceramic plant makes use of local clay and produces facing bricks. The plant is located in Maastricht and the production capacity was increased from 20 million bricks to 23 million bricks in 2018 (L1mburg, 2017). The plant’s manufacturing process uses both manual and mechanical moulding, and has an intermittent kiln with a firing period of nearly two weeks per load of bricks (Steenfabriek Klinkers B.V., 2020).

1.2.6 Gouda Refractories B.V.

In 1901, the brothers Gerhard and Arie Jacob Nagtegaal started a plant for the production of refractory bricks, located in Gouda. At that time the name of their company was Firma Gebrs. Nagtegaal which lasted until 1959, when the company started a partnership with the company De Porceleyne Fles. The new name of this partnership was NV Gouda Vuurvast. In 2008, Gouda Vuurvast became part of the RijnDijk Group (Andus Group since 2009) and the name changed to Gouda Refractories B.V. (Gouda Refractories B.V., 2020).

Currently the total production is 95,000 tonnes per year, consisting of 65,000 tonnes stone, 5,000 tonnes prefab and 30,000 tonnes concrete. These production numbers are based on 50 different types of bricks and 400 different types of concrete. The company employs 150 people and has an annual net revenue of 50 million Euros (Gouda Refractories B.V., 2017; Gouda Refractories B.V., 2020). The firing of the refractory bricks takes place in three tunnel kilns, a continuous process with a duration of a few days per batch of products (Van Ede, 2015). In 2018, new land was acquired (in total 15,000 m^2) next to the plant. This enabled the realisation of new projects like a modern lab and a new office (Gouda Refractories B.V., 2018).

1.2.7 Koninklijke Mosa B.V.

Since 1883, ceramic products have been manufactured at Koninklijke Mosa B.V. (Mosa) in Maastricht. Initially only wall tiles (and other products like imitated porcelain) were produced, but at the end of 1957 the company built a new plant for the production of floor tiles. Currently, the company owns two plants in Maastricht: Locatie Vloertegel (floor tiles) and Locatie Wandtegel (wall tiles), that produce more than 3,000 different types of tiles. The tiles production consists of an equal amount of floor and wall tiles. In addition to its two plants, Mosa owns several selling points in foreign countries and two warehouses, located in Beek and Brunssum. These warehouses have installed PV solar panels on the roof tops to help meet Mosa's target to use 100% green electricity (Koninklijke Mosa B.V., 2017, pp. 30, 58). Mosa has installed fast firing roller kilns 2014, in which the tiles are placed horizontally. These kilns replaced the old tunnel kilns where tiles were placed vertically in batches (Koninklijke Mosa B.V., 2017, p. 57).

The total number of employees is 600, of which 500 are employed in the Netherlands and 100 work in foreign selling offices (Bouwkroniek, 2018). The net revenues were just over 100 million Euros in 2016 (Koninklijke Mosa B.V., 2017, p. 40).

1.2.8 Steenfabriek de Rijswaard B.V.

Originally named the Stoom Pannen- en Steenfabriek de Rijswaard, the plant Steenfabriek Rijswaard was founded by F. Ridder de Huyssen van Kattendijke in Aalst in 1900. Fifteen years later, it became a limited liability company (N.V), and in 1952 the family Blei became owner of the plant which it still is today (Stichting Historie Grofkeramiek, 2020; Van Weezel, 2011). The production capacity is 130 million bricks, and the plant employs 45 people, including the plant, technical facilities and office (Steenfabriek de Rijswaard B.V., 2020). Since 2008, the plant produces its facing bricks through a new 225 meters long tunnel kiln after drying them in one of the 12 drying chambers (Brabants Dagblad, 2008). Furthermore, in 2019 the plant has covered its stockyard by a roof with solar panels (Steenfabriek de Rijswaard B.V., 2020).

1.2.9 Rodruza B.V.

The company Rodruza B.V. was founded in 1986 and currently has approx. 100 employees (Graydongo, 2020). Two of its plants are included in this report, both producing facing bricks: Steenfabriek Rossum, built in 1837 and Steenfabriek de Zandberg (located in Gendt Gld.), built in 1874. Formerly, both plants were owned by the family Terwindt that also owned the plant Steenfabriek Huissenswaard (Stichting Historie Grofkeramiek, 2020; Stichting Historie Grofkeramiek, 2020).

1.2.10 Steenindustrie Strating B.V.

Since 1855, bricks are manufactured at the plant currently known as Steenfabriek Strating. This plant is located in Oude Pekela (RTV Noord, 2018). The plant was founded by Hilbrandie and Holtman, who chose this location due to the wide availability of peat as firing fuel in the surrounding area. In 1883, the plant was acquired by Geert Strating and it has remained a family company until today. The main product of Steenfabriek Strating are facing bricks, shaped by an extruding technique and fired in a tunnel kiln which has been installed at the end of the twentieth century (Steenindustrie Strating B.V., 2020). After the financial crisis was over, the plant was able to increase its production numbers. In 2018, it produced 450 thousand bricks per week (approx. 20 million per annum) and planned to scale up to 600 thousand bricks per week (approx. 30 million per annum). The number of employees in 2018 was 26, and the total revenues nearly 5 million Euros (RTV Noord, 2018).

1.2.11 Vandersanden Nederland B.V.

The history of brick manufacturer Vandersanden goes back to 1925, when Jaak Vandersanden built a small brick plant located in Spouwen, Belgium. The company was expanded with another brick plant in 1962, which included more modern techniques such as the firing taking place in a tunnel kiln. In the following decennia, several plants were built and taken over, all located in Belgium until the beginning of 2005, when Vandersanden expanded its business to the Netherlands by starting a joint-venture with HUWA. The plants included in this joint-venture were Steenfabriek Hedikhuizen (hand-moulded facing bricks), Steenfabriek Spijk and Steenfabriek Huissenswaard (located in Angeren). Steenfabriek Hedikhuizen was rebuilt from 2006 to 2007 with modern facilities and a new production capacity of 75 million bricks per year (Vandersanden Nederland B.V., 2020; Caprice Holding B.V., 2020).

Two year later, in 2009, the joint-venture came to an end when Vandersanden acquired all shares of Steenfabriek Hedikhuizen and Steenfabriek Spijk, and HUWA received full ownership over Steenfabriek Huissenswaard. Moreover, this acquisition also included the brand name 'HUWA baksteen' of the bricks, therefore the company HUWA renamed its company to Caprice Holding B.V., with its plant Steenfabriek Huissenswaard producing 'Caprice baksteen' bricks starting on the first of January 2010 (Caprice Holding B.V., 2020).

At the end of 2016, Vandersanden took over CRH Clay Division Netherlands, Germany and Belgium, all entities of the Irish CRH Group. In the Netherlands, three brick plants were included in this acquisition: Firstly, currently the largest plant in the Netherlands, Kleiwarenfabriek Bylandt Tolkamer, manufacturer of paving bricks. Secondly, Kleiwarenfabriek Bylandt Kessel also known Steenfabriek Joosten, manufacturer of facing and paving bricks and thirdly Steenfabriek Façade Beek, manufacturer of facing bricks. This acquisition made Vandersanden Nederland B.V. the Dutch market leader in paving bricks. In addition, it could now produce facing bricks by an extrusion shaping technique, named: 'strengpers stenen'. The number of employees in the Netherlands became 275 (of 600 in total). The total annual revenues are around 160 million Euros in total, of which approximately 70 million Euros in the Netherlands (Vandersanden Nederland B.V., 2016).

Steenfabriek Hedikhuizen has installed 9700 solar panels on its roof by 2018, which has a peak power of 2.6 MW. Steenfabriek Spijk installed nearly 6000 solar panels on its roof (Brabants Dagblad, 2018). The total amount of 15 thousand solar panels required an investment of 3.6 million Euros which was possible with the help of SDE+ subsidies from the Dutch government (Solar Magazine, 2019). Steenfabriek Hedikhuizen annual consumes around 6.6 million m^3 natural gas and approximately 5.5 million kWh (19.8 TJ) electricity. Around 35% of the electricity is supplied by its 9700 solar panels (Gemeente Heusden, 2019).

1.2.12 Wienerberger B.V.

Wienerberger B.V. is a world leader in ceramic manufacturing by producing bricks, roof tiles, pipes and other building materials. The company was founded in 1819 by Alois Miesbach. Originally, the company was only active in Austria. In 1860 the first chamber kilns were installed (replacing field kilns). This enabled a continuous operation and resulting from this, and other innovations, Wienerberger became the market leader in Austria. The company kept its businesses inside Austria's borders until the end of the twentieth century, when the company expanded into Europe, including the Netherlands (Wienerberger B.V., 2020). The expansion of Wienerberger B.V. within the Netherlands resulted in 19 production locations. Facing and/or paving bricks are produced by 13 plants, three plants produce roof tiles and one plant produces inner wall bricks (Poriso). The total number of employees in the Netherlands is 859 by December 31, 2019, and the annual net revenues are around 200 million Euros (Wienerberger B.V., 2019; Cobouw, 2018). This report includes 18 production locations of Wienerberger B.V. (the plant Wienerberger Panningen is not included).

In 2018, Wienerberger B.V. acquired the company Daas Baksteen that was the owner of three plants, two located in Azewijn and one located in Winterswijk. Note that the two plants located in Azewijn, Steenfabriek de Nijverheid and Steenfabriek de Volharding, are registered at the same address and are registered in the EU ETS by the name: Steenfabriek de Nijverheid (Gelderlander, 2018). Therefore, only 17 plants of Wienerberger B.V. are listed in this report. The plant located in Bemmel is the only plant of Wienerberger that fires its bricks by the traditional use of coal in 24 connecting firing chambers (Wienerberger B.V., 2020). However, in 2012 a newsletter of Stichting Historie Grofkeramiek states that the bricks are fired with natural gas and occasionally coal is added (Stichting Historie Grofkeramiek, 2012).

With regards to energy efficiency, Wienerberger states that several locations already have decreased their use of electricity or natural gas. For instance, the plant in Bemmel did a heat scan through the plant to see where heat is 'leaking'. Kijfwaard West applies smart drying (monitoring moisture levels and temperature) and has replaced its ventilation fans by more efficient blades (Wienerberger B.V., 2019, pp. 19, 20).

1.3 Estimated production volumes and EU ETS CO_2 emissions per location

An estimation of the production volumes in 2016 of the production locations is provided in Table 2. The estimated production capacity and the registered EU ETS emissions in 2016 is also provided. The production volumes were derived from the EU ETS emissions (see for more information regarding the calculation method Appendix A).

The total CO_2 emissions for the ceramic industry that are derived from the EU ETS emissions were quite similar for the past few years, fluctuating closely around 500 thousand tonnes per year. Comparing these emissions with the total annual emissions of Dutch companies registered at the EU ETS shows that the ceramic industry is responsible for less than 0.6% (see Table 1). Mostly bricks are produced (85% of total production), of which facing bricks (placed in the outer wall of a building) cover more than half of the ceramic production in the Netherlands.

Table 1. Total annual CO_2 emission numbers for the ceramic industry in the Netherlands and percentage of total emissions in the Netherlands (EU ETS, 2020)

Year	2015	2016	2017	2018	2019
tCO_{2eq} emissions	477,308	489,757	497,589	519,006	500,134
% of Dutch ETS emissions	0.51	0.52	0.54	0.59	0.60

Table 2 provides an overview of the calculated production for 2016, production capacity, and EU ETS registered greenhouse gas (GHG) emissions (CO_{2eq}) for 2016. Both the calculated production and production capacity are rounded to the nearest 5 kt. The total yearly production capacity of the companies in the table is estimated to be approximately 3.4 million tonnes.

The calculated production values are based on limited available public data (see Appendix A) and are given as ranges. Both the production capacity and production values have not been confirmed by the Dutch ceramic industry and should be treated as indicative values.

Table 2 Overview of all production plants covered in this report, including their company, location, main product, calculated production, calculated production capacity and EU ETS registered CO_{2eq} emission (Dutch emissions authority, 2020).

Name plant	Owner	Location	Main product	Production (2016) kt [5]	Production capacity kt/y	tCO_{2eq} emissions (2016)
Dakpannen-fabriek Woerden	Monier B.V.	Pannenbakkerijen 1, Woerden	Roof tiles	55 to 65	70	10,359
Dakpannen-fabriek Tegelen	Monier B.V.	Steenweg 29, Tegelen	Roof tiles	55 to 70	75	11,091
Steenfabriek Huissenswaard	Caprice Holding B.V.	Scherpekamp 3, Angeren	Facing bricks	110 to 135	150	21,585
Steenfabriek Helden	Engels Baksteen	Steenstraat 8b, Panningen	Facing bricks	90 to 110	130	18,001
Steenfabriek Oeffelt	Engels Baksteen	Kruispunt 26, Oeffelt	Facing bricks	70 to 90	110	14,149
Steenfabriek Linssen	Euro-Steenhandel B.V.	Drievogelstraat 80, Kerkrade	Facing bricks	10 to 15	30	2,328
Steenfabriek Klinkers B.V.	Steenfabriek Klinkers B.V.	Brusselseweg 700, Maastricht	Facing bricks	45 to 55	60	8,756
Gouda Refractories B.V.	Gouda Refractories B.V.	Goudkade 16, Gouda	Refractory products	25 to 35	65	7,855
Locatie Wandtegel	Koninklijke Mosa B.V.	Meerssenerweg 358, Maastricht	Wall tiles	35 to 45	50	19,601
Locatie Vloertegel	Koninklijke Mosa B.V.	Bersebastraat 11, Maastricht	Floor tiles	40 to 45	50	11,830
Steenfabriek de Rijswaard B.V.	Steenfabriek de Rijswaard B.V.	De Rijswaard 2, Aalst (Gld.)	Facing bricks	175 to 210	240	33,864
Steenfabriek Rossum	Rodruza B.V.	Maasweg 1, Rossum	Facing bricks	85 to 105	115	16,715
Steenfabriek de Zandberg	Rodruza B.V.	Polder 8, Gendt	Facing bricks	70 to 85	95	13,611

5 The production value for Gouda Refractories refers to the year 2015.

Name plant	Owner	Location	Main product	Production (2016) kt [5]	Production capacity kt/y	tCO_{2eq} emissions (2016)
Steenfabriek Strating	Steenindustrie Strating B.V.	Gelmswijk 4, Oude Pekela	Facing bricks	20 to 25	35	4,321
Kleiwaren-fabriek Bylandt Tolkamer	Vandersanden Nederland B.V.	Bijland 5, Tolkamer	Paving bricks	175 to 210	235	34,056
Steenfabriek Spijk	Vandersanden Nederland B.V.	Spitsedijk 24, Spijk	Paving bricks	145 to 175	195	28,453
Steenfabriek Hedikhuizen	Vandersanden Nederland B.V.	Bokhovenseweg 8, Hedikhuizen	Facing bricks	75 to 95	140	14,980
Kleiwarenfabriek Bylandt Kessel	Vandersanden Nederland B.V.	Kanaalweg 1, Kessel	Paving bricks	35 to 45	50	7,001
Kleiwarenfabriek Façade Beek	Vandersanden Nederland B.V.	Stationsstraat 106, Beek	Facing bricks	45 to 55	60	8,477
Steenfabriek Poriso	Wienerberger B.V.	Kranenpool 4, Brunssum	Inner wall bricks	75 to 95	105	14,985
Steenfabriek Kijfwaard West	Wienerberger B.V.	Kijfwaard 10, Pannerden	Paving bricks	125 to 150	165	24,290
Steenfabriek de Nijverheid	Wienerberger B.V.	Terborgseweg 30, Azewijn	Facing bricks	105 to 130	145	20,723
Steenfabriek Haaften	Wienerberger B.V.	Crob 3, Haaften	Facing bricks	60 to 70	80	11,477
Steenfabriek Zennewijnen	Wienerberger B.V.	Waalbandijk 18, Zennewijnen	Paving bricks	85 to 105	115	16,547
Steenfabriek Erlecom	Wienerberger B.V.	Erlecomsedam 110, Erlecom	Facing bricks	75 to 90	100	14,797
Steenfabriek Wolfswaard	Wienerberger B.V.	Wolfswaard 2, Opheusden	Facing bricks	75 to 95	100	14,834
Steenfabriek Thorn	Wienerberger B.V.	Meers 38, Thorn	Facing bricks	55 to 70	75	11,145

Name plant	Owner	Location	Main product	Production (2016) kt [5]	Production capacity kt/y	tCO_{2eq} emissions (2016)
Steenfabriek Kijfwaard Oost	Wienerberger B.V.	Kijfwaard 10, Pannerden	Paving bricks	60 to 75	85	11,990
Dakpanfabriek Janssen-Dings	Wienerberger B.V.	Kaldenkerkerweg 11, Tegelen	Roof tiles	60 to 70	80	11,478
Dakpanfabriek Narvik Deest	Wienerberger B.V.	Munnikhofse-straat 4, Deest	Roof tiles	40 to 50	55	7,996
Steenfabriek de Vlijt	Wienerberger B.V.	Misterweg 174, Winterswijk	Facing bricks	45 to 55	60	8,886
Steenfabriek Heteren	Wienerberger B.V.	Steenoord 16, Heteren	Paving bricks	40 to 50	55	8,174
Steenfabriek Schipperswaard	Wienerberger B.V.	Prins Willemsweg 1, Echteld	Paving bricks	25 to 30	35	5,148
Dakpanfabriek Narvik Tegelen	Wienerberger B.V.	Trappistenweg 7, Tegelen	Roof tiles	45 to 55	60	8,499
Steenfabriek Nuance	Wienerberger B.V.	Heukelom 4, Afferden (L.)	Facing bricks	30 to 40	45	6,317
Steenfabriek Bemmel	Wienerberger B.V.	Buitenpolder 10, Haalderen	Facing bricks	30 to 35	35	5,438
Steenfabriek Douveren (recently closed)	Douveren	Wolfsweg 75, Eygelshoven	Facing bricks	<5	Unknown	73

2 Ceramic production processes

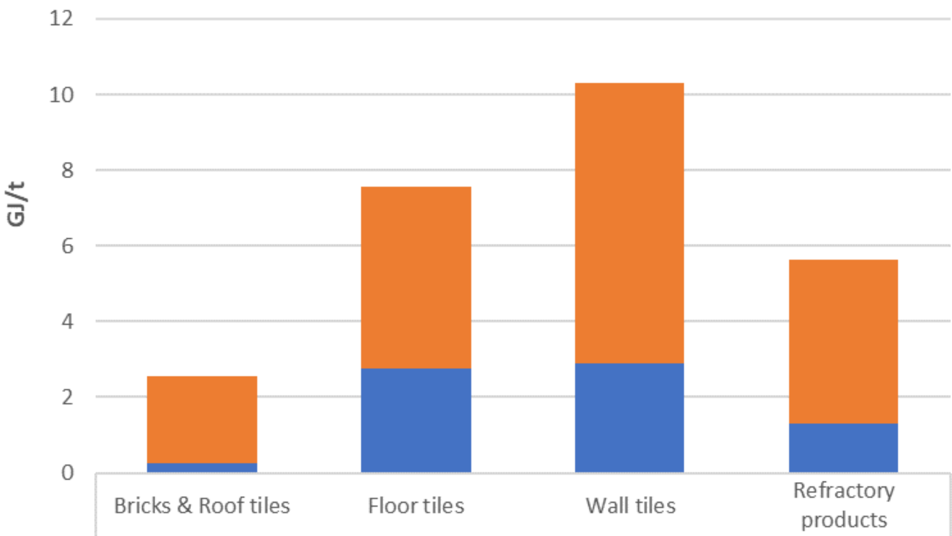
The production of ceramics is divided into four categories, based on the defined categories by the BREF for the ceramic industry (EC, 2007) that are relevant to ceramic manufacturing in the Netherlands:

- Bricks and roof tiles,
- Floor tiles;
- Wall tiles;
- Refractory products.

This section provides an overview of the ceramic manufacturing processes. First, section 2.1 elaborates on the general processes from raw material to the end product used for ceramic production, and which of these processes are included in the research of this MIDDEN report. Section 2.1 also discusses the emissions that occur during ceramic production.

Sections 2.2, 2.3 and 2.4 explain the production processes for bricks and roof tiles, wall and floor tiles and refractory products, respectively. At the end of each these sections a figure is provided with the material, energy and CO_2 emissions flows.

Figure 4 provides an overview of the energy input that is required for the ceramic production process of each product category. Note that these values are in part derived from European data (EC, 2007). The energy consumption of Dutch ceramic plants may therefore deviate from Figure 4 whose values should be treated as indicative values.



	Bricks & Roof tiles	Floor tiles	Wall tiles	Refractory products
Natural gas (GJ/t)	2.31	4.78	7.43	4.35
Electricity (GJ/t)	0.25	2.77	2.89	1.30

Figure 4. Energy input per fuel per tonne product of each category, based on the analysis in the chapter and Appendix A.

2.1 General description of production processes and emissions

2.1.1 Production processes

The manufacturing process of ceramic products is subdivided in six general process steps (see Figure 5): mining and storage, preparation, shaping, drying, firing and subsequent treatment. Only processes taking place within the plants are covered in this MIDDEN report. The first block, 'mining and storage', will therefore be shortly described in this section but is not included in this research in terms of energy consumption.

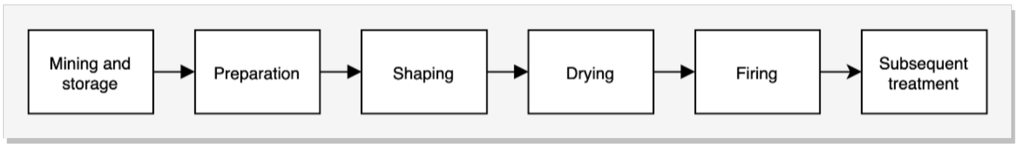


Figure 5. General overview production processes ceramic plants.

Before the manufacturing process, raw material needs to be mined or quarried. In the Netherlands, clay material is often extracted from embanked floodplains. These clay minerals, named 'plastic clays', consist of single or more clay types that are hydrated aluminium silicates resulting from the weathering of rocks. The aluminium silicates are often formed by condensing two structural units: silica sheets and aluminium hydroxide (or gibbsite sheet). The exact properties and related characteristics like plasticity and water content of these raw materials differ per location from where it is extracted. Furthermore, mineral modifiers, named non-plastics, are used as raw material. These can already be in the extracted clay (e.g. red clay due to iron oxide content) or added later in the preparation process (EC, 2007, pp. 13, 14). Figure 6 shows a storage yard where extracted clay can be stored.

The first manufacturing process within the plant is preparation of the clay raw material. This includes increasing the water content for higher plasticity and addition of supplementary materials. Furthermore, different types of clay raw material may be mixed. The exact preparation differs per product and will be explained more in detail in sections 2.2, 2.3 and 2.4.

Pre-dried material (also named 'green ware' (EC, 2007, p. 229)) is shaped into the desired dimensions of the end product, taking into account that the material will shrink during drying and firing. Shaping is performed mechanically by all plants in the Netherlands with different techniques. Examples of such techniques are mechanical moulding, hydraulic pressing and extruding.

The shaped green ware is dried at temperatures ranging from 70 to 90 degrees Celsius. Part of the required heat is provided from hot air extracted from the firing process. The most important aspect of the drying process is to remove water (decreasing the content to less than 1%) from the green ware. If this is not done accordingly, the shaped green ware risks to crack during the firing process. Evaporated water from the drying process is condensed and used to increase the moister content of the raw materials. In addition, water for cleaning machines is filtered to be re-used. As a result, the plants have a nearly closed water system.

Firing of the shaped green ware takes place in intermittent or continuous kilns. Before firing, the shaped green ware is placed or stacked in specific patterns to create a batch of products that can simultaneously be fired. The temperature reached at maximum firing is more than 1000 °C. The required temperature depends on the sintering stages, breakdown of the lattice structures of the clay raw material, followed by recrystallisation and glassy phases (vitrification) (EC, 2007). The main fuel used for reaching this firing temperature is natural gas, which is mixed with air before entering the burner system. The added air might be preheated to save energy (TCKI, 2020). After the maximum temperature has been reached, the fired product is cooled down by clean air, which becomes hot air and is ventilated to the drying process.

The last general process step, 'subsequent treatment', ends at the stockyard ('tasveld' in Dutch) or warehouse of the plant, where packaged end products are stored. Any material of product losses from the first to last process step are recycled by most plants. The specific processes for the different ceramic products are explained in more detail in sections 2.2, 2.3 and 2.4.

Figure 6. Storage yard (in Dutch 'kleidepot') where extracted clay is stored, often closely located to the ceramic plant (KNB, 2020).

2.1.2 Emissions

CO_2 is emitted during ceramic production from burning fuels like natural gas (fuel emissions), or from chemical reactions of carbonates (process emissions, see Figure 7). These chemical reactions are also referred to as calcination.

$$
\begin{array}{lcl}
3Fe_2O_3 + CO & = & 2Fe_3O_4 + CO_2 \\
1Fe3O_4 + CO & = & 3FeO + CO_2 \\
1Fe2O_3 + CO & = & 2FeO + CO_2 \\
1FeS + 1.5\ O_2 & = & 1FeO + SO_2 \\
1CaCO_3 & = & 1CaO + CO_2 \\
1MgCO_3 & = & 1MgO + CO_2
\end{array}
$$

Figure 7. Chemical reactions resulting in process emissions (EC, 2007, p. 58).

The amount of process emissions depends on the raw materials used and can therefore differ significantly between plants, despite producing the same type of products.

The three main processes that emit fuel related CO_2 are: spray drying (only wall and floor tiles), drying[6] and firing. These three processes are assumed to all use natural gas as energy source. Figure 8 states the calculated average CO_2 emissions per tonne end product. At the end of each of the sections below, energy and material flow diagrams are given that include the CO_2 emissions numbers for each category in more detail. Note that the emission numbers rely on general European process data (EC, 2007) as a source. The specific CO_2 emissions of Dutch ceramic plans may therefore deviate from Figure 8.

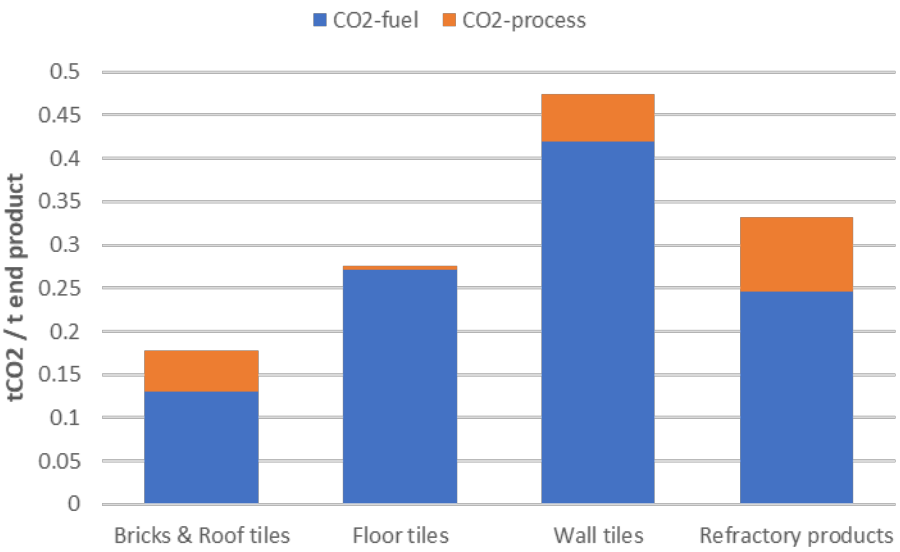


Figure 8. CO_2 emissions per tonne of end product per product type. Blue part of the bar are emissions from burning fuels and orange part are the process emissions. This graph is based on the analysis in this chapter and Appendix A.

In addition to CO_2 emissions, fluorine, chlorine, sulphur and nitrogen oxides (NO_x, including both NO and NO_2) emissions are present during the manufacturing processes. Currently, these emissions are reduced via flue gas treatment installations. Together with other adjustments, this has reduced the fluorine emissions by 80% between 1993 and 2000. Therefore, these emissions are currently in compliance with the Dutch emission guidelines (KNB, 2020).

6 Some plants may use CHP installations to supply the required additional heat to the drying process.

2.2 Brick and roof tile production process

The manufacturing processes of the bricks and roof tiles is represented by 33 plants in this report, 28 brick (facing, paving and inner wall bricks) manufacturers and 5 roof tile manufacturers (Figure 9). Some plants produce more than one type of brick, e.g. both facing and paving bricks. For these cases, their main product is taken as reference for their type of production (for more information per plant see Table 2).

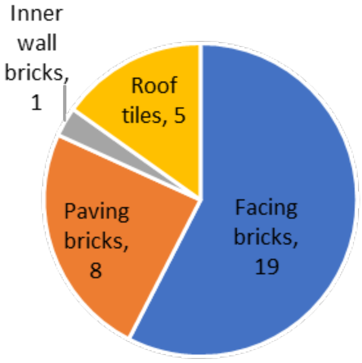


Figure 9. Number of plants producing bricks or roof tiles. The total production capacity of these plants together approximates 3,200 thousand tonnes (see Table 2).

This section describes the general processes for bricks and roof tiles production. The exact processes used by the Dutch ceramic plants may deviate from these general processes.

2.2.1 Production processes

Because the manufacturing processes of both bricks and roof tiles are relatively similar, they are explained here using the same process flow diagram (Figure 10). During the shaping phase, one of three techniques can be applied which determines the characteristics of the end product. Extra treatment is optional in the form of glazing or engobing (a fine-grained layer of ceramic mass). Drying and firing takes place in an intermittent or continuous way.

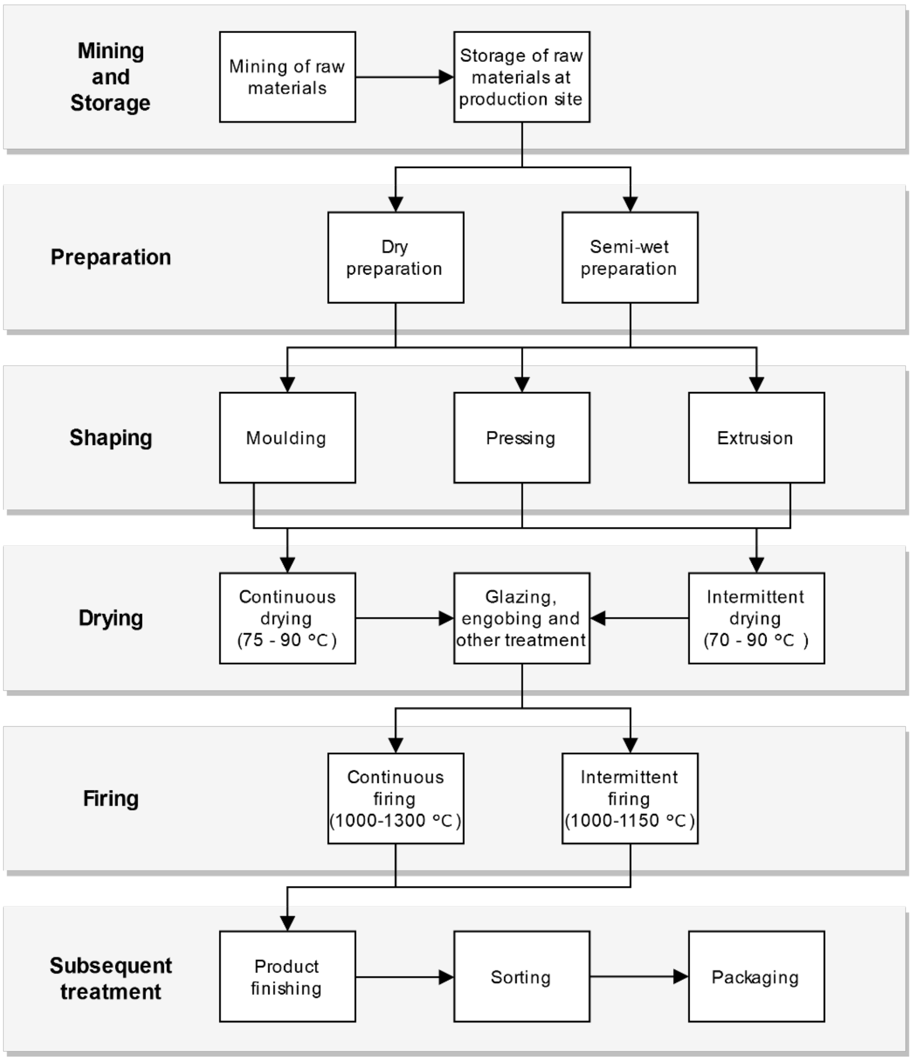


Figure 10. Production processes bricks and roof tile manufacturers.

Preparation

The preparation process is defined as dry or semi-wet, depending on the water content of the material. For the semi-wet preparation process extra water (or sometimes steam) is added. Both dry and semi-wet preparation can be split into three similar parts:

1. Reducing particle size;
2. Adding additives and;
3. Homogenisation of the mass.

For the dry preparation process, with the material having a low plasticity, hammer or roller mills are used to reduce the particle size. During milling, additives are added to maintain a good plasticity (e.g. hydrated lime). In the semi-wet preparation process, with a water content of around 20%, the hard materials are crushed to get a specific particle size (roof tiles need a lower particle size than bricks). The type of crusher depends on the characteristics of the raw material. Sand can be added to this process to improve the moulding, enhance the colour and generate a specific surface texture. In addition, lava, chalk and oxides are added for specific colours (Caprice Holding B.V., 2020).

Both dry and semi-wet preparation need mixing in the end for homogenisation. This is achieved by shredders, mixers or kneaders. The final water content is on average 20% (EC, 2007, pp. 39, 40).

Figure 11. Preparation process of a ceramic plant (KNB, 2020).

Shaping
Three different shaping methods are used by the bricks and roof tile manufacturers in the Netherlands: moulding, pressing and extruding. Each of these methods determines important properties of the end product (e.g. surface irregularities). In brick manufacturing in the Netherlands, different names are given for bricks depending on the used shaping method: 'handvorm' bricks for moulding, 'vormbak' bricks for pressing and 'strengpers' bricks for extruding. In addition, the size of the end product is determined by the shaping process. Due to the differences in sizes, the production of bricks is often expressed in Waal format (WF), which is a standardised size brick with a weight of around 1.84 kg (KNB, 2017).

Moulding (or hand-moulding) is the original method of shaping, dating back more than 10,000 years. Individual clots of clay are, in current days mechanically, thrown in pre-sanded moulds. The moulds are sanded to ensure the moulded piece of clay comes out easily. This method requires relatively little power compared to pressing and extruding, though the clay needs to contain more water than for the other two shaping methods. Because of this, more energy is needed for the drying process to lower the water content (EC, 2007, p. 20). The water content after moulding is 30-35%, according to DOWN TO EARTH BV (DOWN TO EARTH BV, 2013). Some companies use a shaping method named Wasserstrich, which is moulding without adding sand but by wetting the mould with water beforehand (Vandersanden Nederland B.V., 2020; Rodruza B.V., 2020).

Closely related to moulding is the second shaping technique: pressing. The pre-sanded moulds, also named die boxes, are filled with clay and pressed by pistons, usually driven mechanically (EC, 2007, p. 19). A machine used for this technique in The Netherlands is 'De Boer vormbandpers' with 17 moulds that can be used at the same time. This machine can also shape green ware by means of the hand-moulding explained above (Caprice Holding B.V., 2020).

Extrusion, the third technique, is different from the two above techniques because the raw material is extruded through a die instead of shaping it by a mould or die box. Before clay is forced through the die by an extrusion auger, any remaining air in the chamber between the raw material and auger is vacuumed (EC, 2007, p. 20). After extrusion, the formed column is cut into pieces by thin metal wires (Steenindustrie Strating B.V., 2020). The raw material used for extruding bricks is different, because fatter and drier clay is required, resulting in denser bricks with smooth edges. This is also showed by the water content which is only 17-22% after shaping (DOWN TO EARTH BV, 2013). Nevertheless, the temperature in the firing process should be at minimum 60 °C higher than for moulded and pressed bricks (Vandersanden Nederland B.V., n.d.). The extrusion technique can also be used for roof tile production (Bouwtotaal, 2019).

Drying

The drying process can be subdivided in intermittent and continuous drying. According to the BREF, intermittent drying is mainly performed in drying chambers, where drying one batch of green ware lasts up to 40 hours with temperatures from 70 to 90 °C. Continuous drying takes place in tunnel or fast dryers, which can last from less than 8 to close to 72 hours (depending on the length of the tunnel dryer and production rate) and demands temperatures from 75 to 90 °C. The water content after drying should be less than three percent (EC, 2007, p. 41). The hot (clean) air needed for drying comes mainly from the cooling section of the firing process, where bricks are cooled down (see Figure 12). Any additional required hot air is provided by natural gas burners or generated from a gas-fired combined heat and power (CHP) installation. Natural gas is for (almost) all plants the main heating source.

Plants that, according to literature, make use of a CHP are: Steenfabriek de Rijswaard, Steenfabriek Huissenswaard (Caprice Holding B.V., 2020; Steenfabriek de Rijswaard B.V., 2020) and Steenfabriek Spijk (Provincie Gelderland, 2015). Note that it has been confirmed by the Dutch ceramic industry that some plants use a CHP, but it has not been confirmed which plants specifically.

After drying, additional treatment can be applied based on specific client requirements (Bouwtotaal, 2019). Extra treatment can be glazing, engobing (a fine-grained layer of ceramic mass), and other decorating techniques, being applied by dipping or pouring on the surface of the green ware. This treatment is usually applied after the drying process - and sometimes even after the firing process (EC, 2007, p. 23).

Firing

Similar to drying, firing can be applied in an intermittent or continuous matter. Intermittent kilns offer flexibility compared to tunnel kilns and therefore are more suitable for e.g. special shaped bricks or roof tile fittings that are produced in lower numbers (EC, 2007, p. 25). The use of chambers also enables a batch of roof tiles to be closed off from oxygen (and add nitrogen) resulting in a blue coloured end product. This is named ‘smoren’ in Dutch (Bouwtotaal, 2019).

Most of the brick and roof tile plants in the Netherlands are assumed to make use of continuous tunnel kilns. As shown by Figure 12, each batch of bricks is pushed or pulled through three phases within a tunnel kiln. First the batch is heated by flue gases (the firing kiln exhaust), then fired by natural gas to reach a maximum temperature for sintering. Finally, the bricks are cooled down.

For efficiency, the process uses a counter-current flow of air to allow cool air to cool down the bricks. The heat air is then partly ventilated away to the drying process and partly moves as hot air towards the firing section. The ratio in thermal energy requirement between drying and firing is roughly 50/50.

In general, plants have flue gas treatment installations in place to filter the flue gases to meet environmental standards for among others, NO_x and fluoride emissions.

A tunnel kiln is usually over 150 meters long and a maximum temperature is reached of 1000 to 1300 °C (EC, 2007, pp. 41, 42; Van Weezel, 2011; Wingas, 2020).

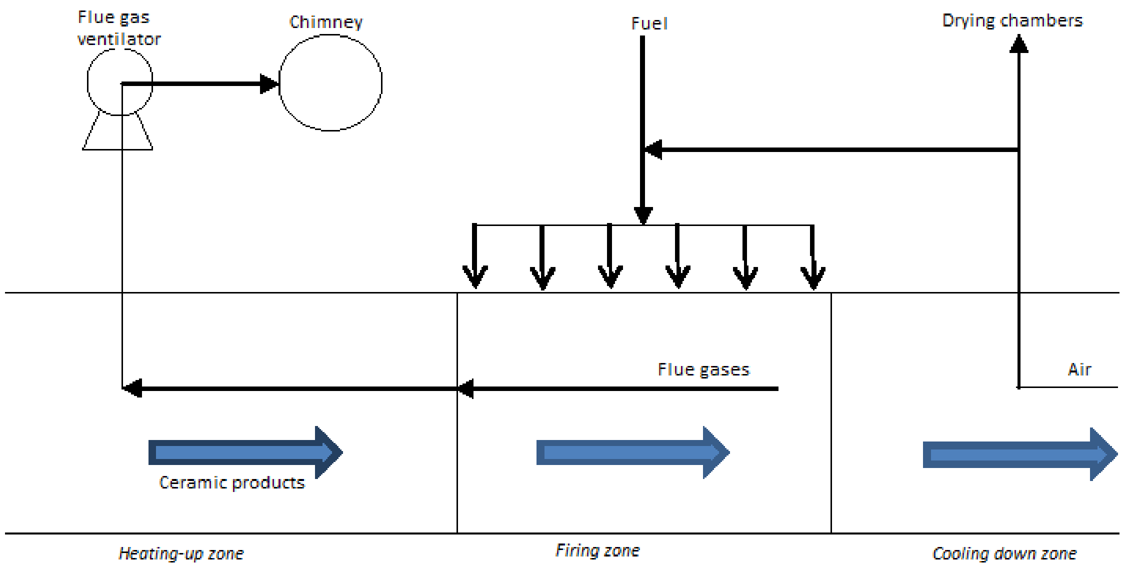


Figure 12. Three phases of the firing process in a tunnel kiln: heating-up, firing and cooling down zone. Source: captured and translated from (Ecosys, 2014, p. 36).

Subsequent treatment

Examples of subsequent treatment are surface smoothing, creation of extra holes that were not possible during the shaping process, and sometimes a retro look is required by the customer. To achieve this, bricks are thrown together in a drum machine to remove sharp edges and decrease similarities.

After any product finishing techniques, the bricks or roof tiles are sorted and packaged (see Figure 13) to be stored at the stockyard, which can be covered by a roof to prevent moisture and algae damaging the finished products.

Figure 13. Packaging machine of bricks (KNB, 2020).

2.2.2 Material, energy and CO_2 emissions flows

Figure 14 provides the material, energy and CO_2 emissions flow diagrams for brick manufacturers and roof tile manufacturers. The calculations and used sources are provided in Appendix A. The use of CHP is not included in the calculations and flow diagrams because this technology is not commonly used. Note that the calculations use European data (EC, 2007). As the energy consumption of the Dutch ceramic mills may deviate, the given values should be treated as indicative values.

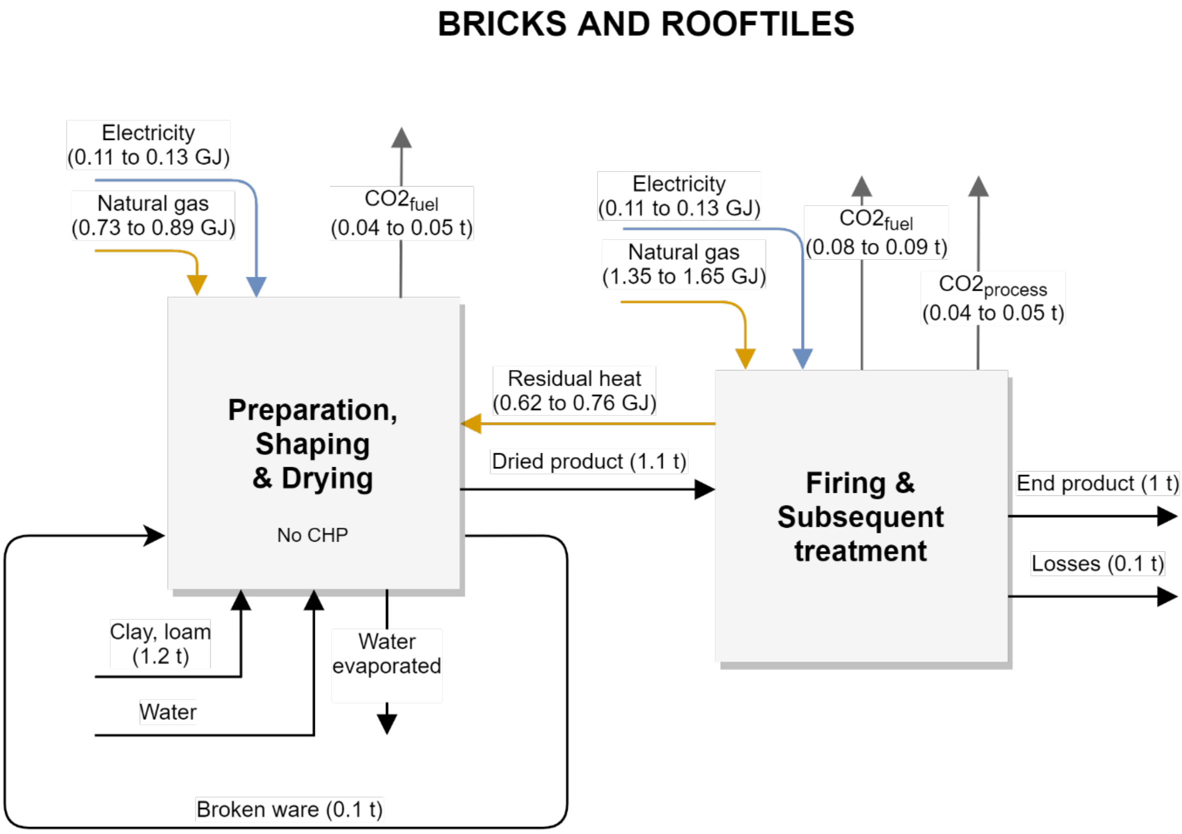


Figure 14. Flow diagram of the manufacturing process of bricks and roof tiles, including material, energy and CO_2 emissions flows. Applicable to plants without gas-fired CHP, steam boilers for drying, or other alternative drying methods.

2.3 Wall and floor tiles production processes

Different processes are used for wall and floor tiles due to the differences in requirements (e.g. frost resistance for outdoor tiles) which requires specific raw materials and extra process steps. This results in two main types of ceramic tiles which both use raw materials like clay, sand, marl, felspar, broken ware and recycled tiles. The first type are pottery tiles (‘aardewerk tegels’ in Dutch) that are mainly used for wall tiles. The second type, ‘porcelain tiles’, are tougher than pottery tiles and have a higher wear resistance. In addition, porcelain tiles are frost resistant, which pottery tiles are not. This makes porcelain tiles applicable to both walls and floors, including high traffic zones like shopping malls.

This section describes the general processes for wall and floor tiles production. The exact processes used by the Dutch ceramic plants may deviate from these general processes.

2.3.1 Production processes

Figure 15 shows the manufacturing processes for floor and wall tiles. The main difference between the two processes is that wall tiles require a double firing process and glazing. Floor tiles only require fast firing to receive full sintering.

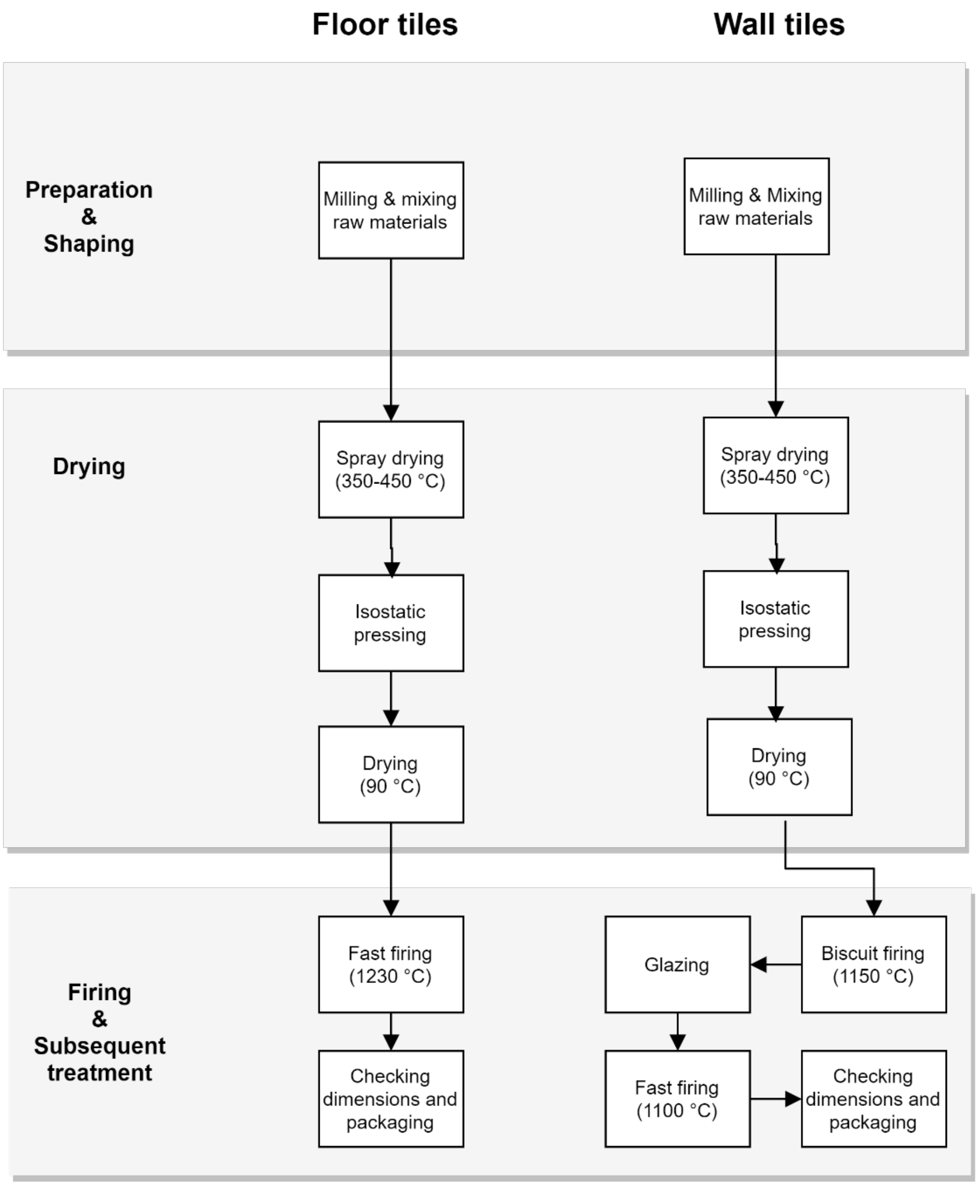


Figure 15. Production processes wall and floor tiles

Preparation and shaping

The raw materials are milled and mixed to reach a homogenized substance. Floor tiles need a different bottom and top layer, so two substances are created for that product.

Drying

To decrease the water content the particle size of the substances are reduced even more by removing embedded water, for which spray drying is applied. This method, taking place before the shaping process, sprays hot air through the substance. As a result, granulation takes place: fine droplets are formed and form highly uniform granules that facilitate accurate filling of the pressing dies. The moisture content decreases from approx. 30% to 6% and the required temperature within the spray dryer is 350-450 °C, requiring an energy consumption of 1.1 – 2.2 GJ/t (EC, 2007, pp. 17, 61, 120).

The shaping of floor and wall tiles, which for floor tiles is in fact adding two layers of substance together, is done by isostatic pressing with a pressure of 400 tonnes per 30x30 cm.

After shaping the tiles, the second step of drying is applied to further decrease the water content. This process is done with a temperature of 90 °C. The drying duration per batch of tiles is three hours (Bouwkroniek, 2018) and the residual water content is less than 1 percent (EC, 2007, p. 62).

Firing and subsequent treatment
Firing takes place in a fast firing roller kiln (also named 'modern roller hearth kiln') with a temperature of up to 1230 °C to ensure the tiles become fully sintered. The tiles are horizontally placed on ceramic rollers instead of the old method where tiles are stacked vertically in tunnel kilns. As shown in Figure 15, wall tiles have an extra process step: biscuit firing[7] and glazing. This is necessary for optimal colouring and shining properties. Whereas floor tiles are immediately fired at a temperature of 1230 °C, wall tiles are first biscuit fired at a temperature of 1100 °C. At the same time the glazing material is prepared, which is a glassy substance that consists of melted feldspars. After the wall tiles are biscuit fired, glazing is applied by moving the tiles through a curtain of glazing. When the glazing has dried, the tiles are another time fired at a temperature of 1100 °C (Bouwkroniek, 2018).

After cooling down, the dimensions of the tiles are adjusted if required and some types of floor tiles could be ground or polished, recycling any material if possible. Finally, the tiles are packaged and stored at one of the warehouses (EC, 2007).

Figure 16. The outside of fast firing roller kilns (KNB, 2020).

7 Initial firing to harden the outer parts of the tile such that glazing can be correctly applied.

2.3.2 Material, energy and CO_2 emissions flows

Figure 17 and Figure 18 show the material, energy and CO_2 emissions flow diagram of floor and wall tiles, respectively. The calculation method of the values in the flow diagrams and used sources are provided in Appendix A. The amount of residual heat extracted from the firing section used for drying could not be determined. Note that the calculations use European data (EC, 2007). As the energy consumption of the Dutch ceramic mills may deviate, the given values should be treated as indicative values.

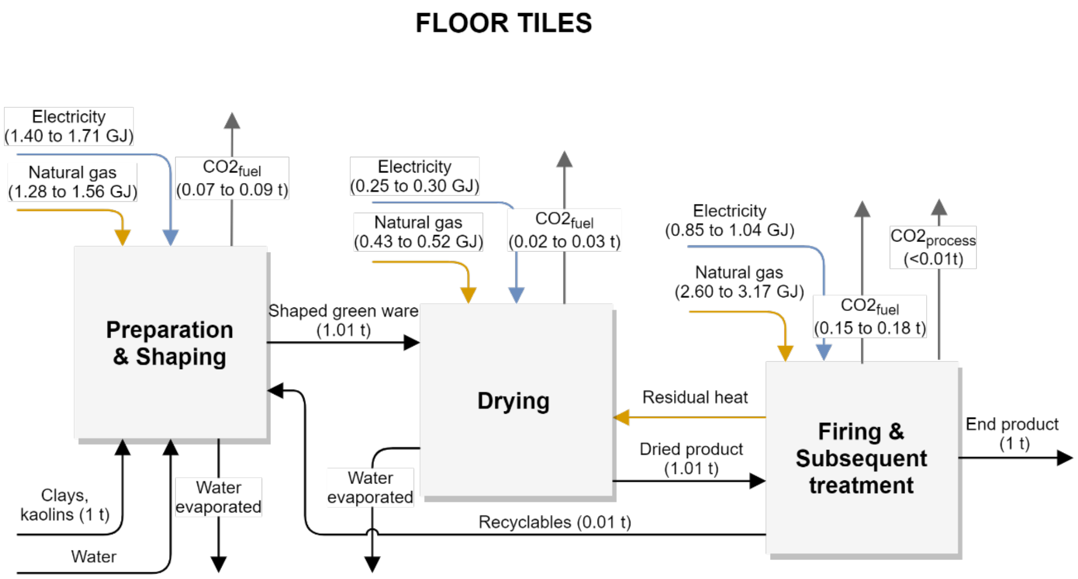


Figure 17. Flow diagram of the manufacturing process of floor tiles, including material, energy and CO_2 emissions flows.

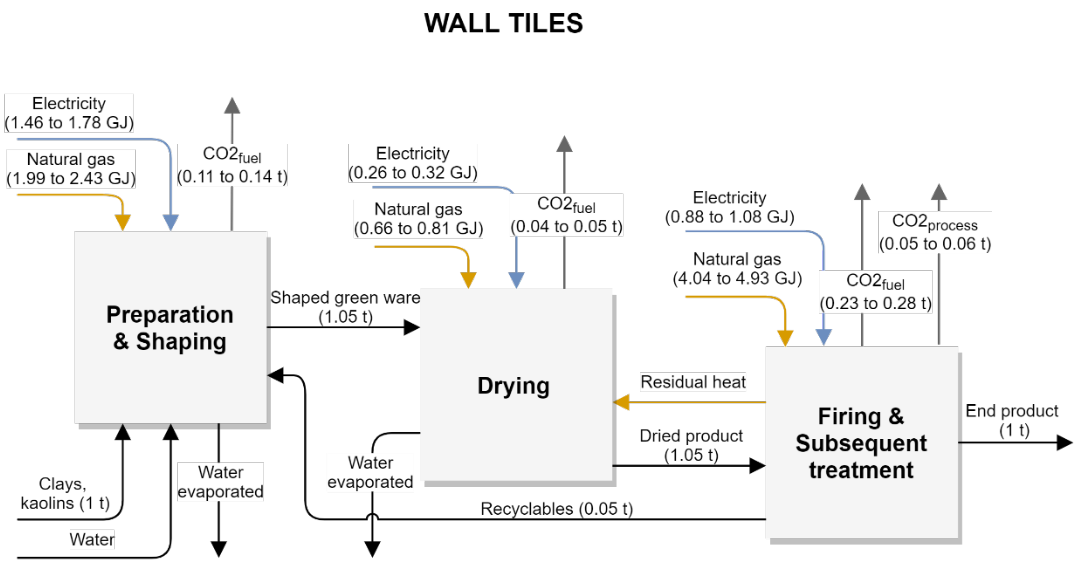


Figure 18. Flow diagram of the manufacturing process of wall tiles, including material, energy and CO_2 emissions flows.

2.4 Refractory products production processes

This section describes the general processes for refractory products production. The exact processes used by the Dutch ceramic plants may deviate from these general processes.

2.4.1 Production processes

First the raw material is milled to predefined particle sizes, then additives are added together and mixed to obtain a homogenized material. In total, 7 to 10 different types of materials and ingredients are used as raw material input. The shaping process is applied by mechanical pressing in moulds and both the drying and firing takes place in tunnel kilns. Both the drying and firing process use natural gas. Drying requires a temperature of 100 °C and firing a temperature of 1700 °C. After the firing process, which takes 2 to 3 days, the refractory product is cooled down and given subsequent treatment based on the customers' requirements (Van Ede, 2015).

2.4.2 Material, energy and CO_2 emissions flows

Figure 19 shows the material, energy and CO_2 emissions flow diagram of refractory products. The calculations and used sources are provided in Appendix A. Note that the calculations use European data (EC, 2007). As the energy consumption of the Dutch ceramic mills may deviate, the given values should be treated as indicative values.

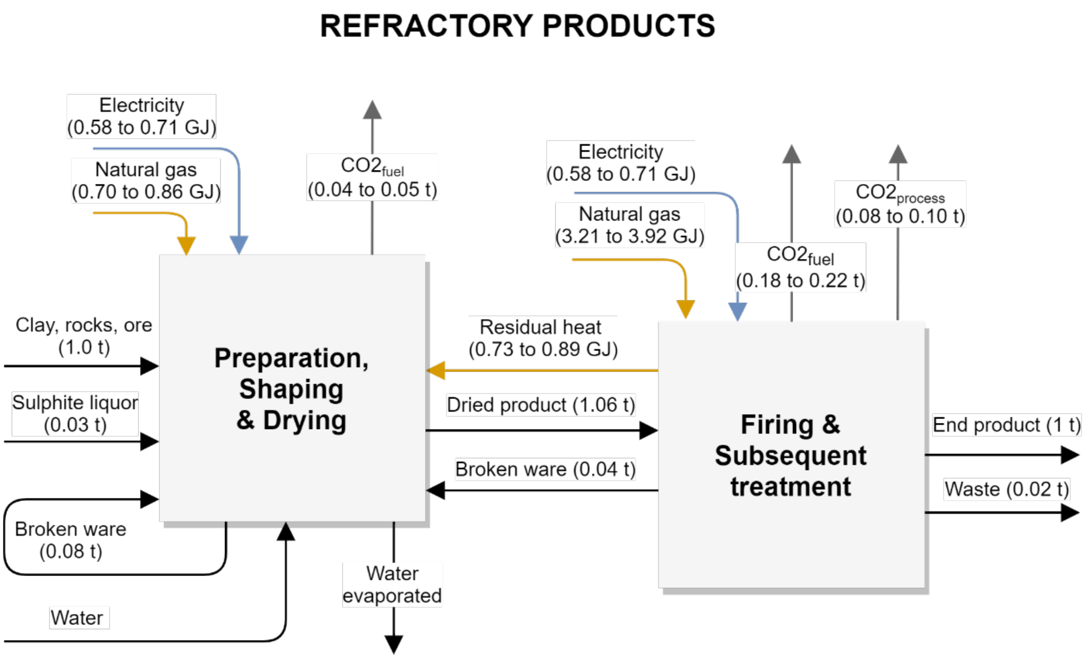


Figure 19. Material, energy and CO_2 emissions flow diagram of refractory products. Material amounts are taken from the BREF example of production of periclase chromite bricks (EC, 2007, p. 112).

3 Ceramic products and applications

This section describes the applications and markets of the Dutch ceramic industry covered by this MIDDEN report.

3.1 Main products and applications

3.1.1 Bricks

Brick products are produced in large quantities and are mostly used in the construction sector. The main subtypes for bricks are facing bricks, paving bricks and inner wall bricks. Facing bricks are commonly used for the external walls of domestic and commercial properties. They are used for surfaces that are exposed to weather conditions. The appearance of such surfaces is important. Inner wall bricks on the other hand are used for the part of the building structure facing inwards. Paving bricks are used to be laid flat on the ground. They are designed specifically to last when installed to withstand all weather conditions.

Figure 20. From left to right: facing bricks, paving bricks, and inner wall bricks. Facing and paving bricks source: (KNB, 2020), inner wall bricks source: (Architectenweb, 2020).

3.1.2 Roof tiles

Roof tiles are designed to withstand harsh weather conditions and are designed specifically to keep out rain. Since the 16th century, hollow roof tiles (‘holle pannen’ in Dutch) are produced in the Netherlands, improved in around 1900 (named ‘verbeterde holle pannen’) followed by another improvement in 1935 which renamed the roof tiles into ‘Opnieuw Verbeterde Holle’ (OVH). These roof tiles have specific dimensions of 36 cm (Bouwtotaal, 2019). Other types of roof tiles are ‘flat’ roof tiles, such as the Tuile du Nord (BMI Monier, 2020), and the ‘tegelpan’, a roof tile that is cross laid (Wienerberger B.V., 2020).

Figure 21. Glazed roof tiles. Source: (KNB, 2020)

3.1.3 Wall and floor tiles

A ceramic tile is a thin and usually square or rectangular object made from clay and other inorganic materials, that is generally used as covering for floors or walls. The tile sides range from a few centimetres to 60 to 100 cm sides. Their thickness can vary from around 5 mm to 25 mm. Maintenance and renovation is an important aspect of ceramic tile usage (EC, 2007).

Figure 22. Floor and wall tiles. Source: (KNB, 2020)

3.1.4 Refractory products

Refractory bricks are used for inner linings of ovens, for example in the steel or glass industry. Due to the high temperatures in such ovens, these bricks must be able to withstand extremely high temperatures. This is already indicated by the high temperatures to fire this product (around 1700 °C), explained in section 2.4. The main users of these refractory products are industrial installations using high temperature processes, such as petrochemical industry, non-ferro producers, and users of combustion installations (Buisman, 2016).

Figure 23. Refractory bricks. Source: (Gouda Refractories B.V., 2020)

3.2 Markets

The Dutch ceramic industry serves both the domestic market as well as other countries that are located nearby. Serving countries further away will not be cost effective for bulk products (i.e. bricks and roof tiles) due to the relatively heavy weight of the products and low value, and competition in countries where clay is also highly available. Ceramic tiles and refractory products, however, are exported globally.

For bricks, exports averaged around 20% of the total annual production in 2014 (RVO, 2014). Especially the UK is an import trading country for the Dutch ceramic industry (RVO, 2014). In 2019, the total sales of the Dutch bricks for the building sector declined. This was the result of the uncertainties concerning Brexit, which affected export results. Another important factor was the debate regarding the nitrogen emission and PFAS[8] deposition policy and its impact on the building sector.

For ceramic tiles, the main application is within buildings in the Netherlands, but also abroad. Export to other European countries, but also North America and countries in the Middle East, is expected to grow considerably.

Aside from the clients in the Netherlands, refractory products are shipped to countries such as the USA, South-Africa, Australia, and Saudi Arabia (Buisman, 2016).

[8] Per- and polyfluoroalkyl substances, a collection of substances that, if present in high concentration in soil, restricts the use of the soil.

4 Options for decarbonisation

The Dutch climate agreement ('Klimaatakkoord') introduced in 2019, has set as a target for the Dutch industrial sector to abate its CO_2eq emissions by 19.4 Mt by 2030 compared to 2015 (Klimaatakkoord, 2019, p. 83). The long-term goal is to reduce the total CO_2eq emissions in the Netherlands by at least 95% compared to 1990 emissions levels (Klimaatakkoord, 2019). In addition to these targets, gas extraction from the Groningen gas reservoirs will be phased out as soon as possible, potentially already in 2022. These developments are relevant for the ceramic production in the Netherlands, which is energy intensive with high temperatures and uses Groningen gas as its main fuel.

For the last decades, energy efficiency improvements have been made in the ceramic sector, accelerated by the MJA-agreements (Meerjarenafspraken), resulting in more efficient kiln designs and drying techniques. In addition, the drying and firing process has become a continuous process (creating a stable energy demand). However, further decarbonisation is required to achieve net zero (fuel) CO_2 emissions. The KNB has constructed a 'Technology Roadmap' (KNB, 2020b). This roadmap will, among others, elaborate on the energy transition and carry out research for the ceramic industry.

Different options for decarbonisation are described in this section, categorised according to the overview in Figure 24. The relevant categories are fuel substitutions, process design, use of residual energy and CO_2 capture and storage (or utilisation).

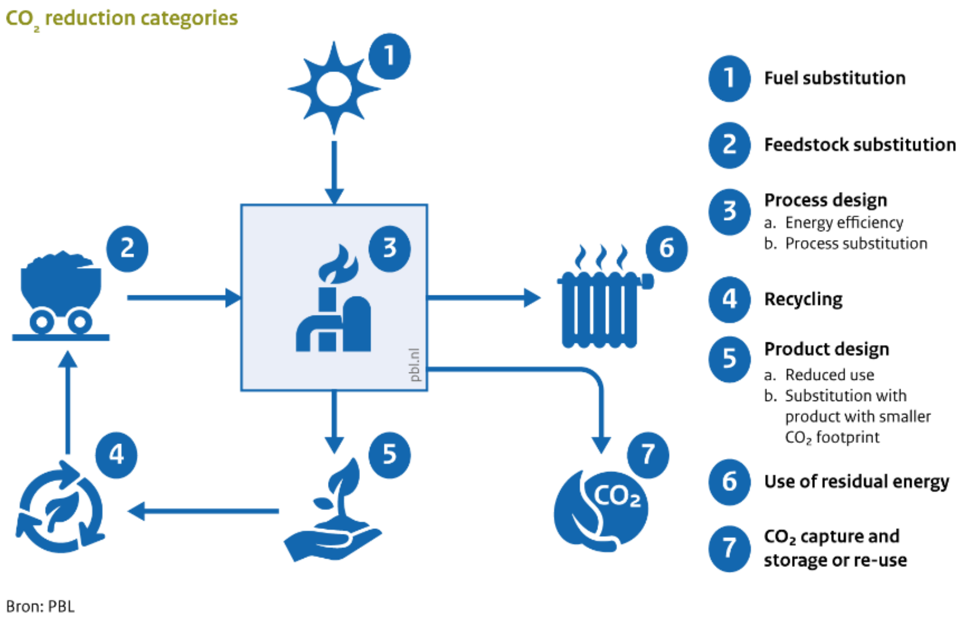


Figure 24. Different CO_2 abatement categories identified by MIDDEN.

Table 3 provides an overview of the different decarbonisation options that are applicable to the ceramic industry in the Netherlands.

Table 3 Overview of abatement options, including the category, relevant process, maximum CO_2 abatement and availability.

Name option	Category	Process(es)	Maximum CO_2 abatement	Availability
Green gas	Fuel substitution	Drying/Firing	74%	Commercially available
Hydrogen	Fuel substitution	Drying/Firing	74%	Lab scale
Electric heating	Fuel substitution	Drying/Firing	74%	Concept
Microwave radiation	Fuel substitution	Drying/Firing	74%	Concept
Heat exchange	Use of residual energy	Drying	26%	Pilot scale
Heat pump	Use of residual energy	Drying	26%	Commercially available (for the relevant temperature)
Hybrid drying	Use of residual energy	Drying	Varies	Pilot scale
Ultra-deep geothermal	Process design	Drying	26%	Commercially available, but not yet in The Netherlands
Extended tunnel kiln	Process design	Firing	26%	Commercially available
CCS or utilisation	CCS or re-use	Firing	90%	Commercially available[9]
Lighter bricks	Product design	Firing	Unknown	Concept

4.1 Fuel substitutions

Alternative carbon neutral fuels such as green gas and hydrogen, and renewable electricity can substitute the natural gas that is used for firing and drying by the ceramic plants in the Netherlands. Stichting Technisch Centrum voor de Keramische Industrie (TCKI)[10] and DNVGL already are testing the impact of hydrogen on a laboratory scale, to measure the impact on the product.

[9] Transport and storage is not available at the locations of the ceramics plant.
[10] An independent research institute, knowledge and support centre in the ceramic industry.

4.1.1 Green gas

Green gas (also named 'biomethane') can directly replace natural gas.

Green gas can be produced using anaerobic digestion or gasification technology. Anaerobic digestion is preferred for wetter biomass material and gasification is preferred for dryer biomass material.

Green gas from gas grid

If green gas is produced on a large scale centrally and inserted into the Dutch gas grid, no changes would be required for the ceramic industry to decarbonise the ceramic production process fuel-related CO_2 emissions, as the natural gas consumption from the grid would be replaced by green gas consumption from the grid.

On-site anaerobic digestion (biogas)

If green gas from the grid is not available, on-site anaerobic digestion could be applied. Anaerobic digestion is a biological process where bacteria break down biomass material in the absence of air. The biogas that is formed is composed approximately of 60% methane and 40% CO_2. The feedstock material for anaerobic digestion is often waste – such as food waste, agricultural waste, waste from water treatment and municipal waste – but can be any type of non-woody biomass. The biogas can then be converted into green gas by removal of non-methane elements (mostly carbon dioxide) (Lensink, 2020). During the digestion process, the required heat is obtained by burning part of the produced biogas. Table 4 shows information about the cost for an installation as described by (Lensink, 2020)

Table 4 Parameters for a large-scale production unit of green gas using digestion. Adapted from (Lensink, 2020, pp. 89, 99).

Parameter	Unit	Value
Green gas production per year	GJ	150,000
Investment costs	M€$_{2019}$	6.9
Fixed O&M costs per year	M€$_{2019}$	0.6
Feedstock (waste) costs	€$_{2019}$/GJ	8.18[1]

[1] Assuming cost of feedstock of 27.8 €/t and energy density of 3.4 GJ/t (Lensink, 2020, pp. 89).

On-site gasification of biomass (syngas)

If green gas from the grid is not available, on-site gasification could also be applied. Gasification of biomass (organic material) is a thermochemical process that produces syngas. The syngas is composed of methane, hydrogen, CO and CO_2 and is used as fuel or feedstock, and can also be upgraded into green gas. Producing syngas at the site of a ceramic plant would require a 'bio-SNG-centrale' that produces green gas in three steps: First, gasification takes place, then the gas is cleaned from unwanted elements, and finally it is upgraded conform to the quality standards of natural gas. Table 5 shows the associated parameters and costs for production of green gas by gasification of biomass for a reference installation as defined in (Lensink, 2020).

Table 5 Parameters for a production unit of green gas using gasification of biomass. Adapted from (Lensink, 2020, p. 77).

Parameter	Unit	Value
Green gas production per year	GJ	567,000[1]
Investment costs	$M€_{2019}$	56.7
Fixed O&M costs per year	$M€_{2019}$	3.99
Feedstock (biomass) costs	$€_{2019}$/GJ	5.00[2]

[1] Power output is 21 MW * 7,500 operational hours per year* 3.6 GJ/MWh = 567,000 GJ/yr.

[2] Cost of fuel is 45 €/t and energy density of fuel is 9 GJ/t (Lensink, 2020, p. 77).

4.1.2 Hydrogen

Hydrogen is a fuel substitution but, unlike green gas, it does require a few adjustments to the manufacturing process. The applicability of hydrogen depends on the firing kiln design, and will also require investments in modified burners. Firing by hydrogen results in higher temperatures, which leads to an increase in NO_x emissions. This, and the potential negative impacts of the fuel switch on the product quality requires further research before hydrogen can be considered fully applicable as fuel substitution.

Hydrogen fuel can be categorised based on their production process: grey hydrogen, blue hydrogen, green hydrogen, by-product of other production processes. Grey hydrogen is produced via steam methane reforming (SMR) with natural gas as fuel and is therefore not fossil free. Blue hydrogen is also produced via SMR, but combined with capturing and storing of related carbon emissions. Green hydrogen is producing hydrogen via electrolysis[11]. Green hydrogen production is currently three times more expensive as producing grey hydrogen (Elzenga & Lensink, 2019).

Only hydrogen that is centrally produced and can be extracted from a national grid is considered in this study. On-site production of blue or green hydrogen is not considered as an option. The existing gas infrastructure (i.e. pipelines and storage tanks) can potentially be used when the natural gas is fully substituted by hydrogen, with only a few adjustments required due to the lower density of hydrogen (Gasunie, 2018). It is unknown if and when large amounts of green hydrogen will be produced and inserted into the gas grid.

The TCKI has done research regarding the application of hydrogen in the ceramic industry (TCKI, 2019), and has concluded the following:

- Transporting hydrogen instead of natural gas through pipelines has a capacity loss of only 10% in terms of energy.
- 58% more water content in flue gases (might be an opportunity in recovering latent heat).
- Less environmental air is needed for mixing before hydrogen enters the burning installation.
- No problems will occur with reaching the desired flame temperature.
- When firing frequency is high enough, flame strikes are prevented.

It is currently unclear what burner modifications are needed (further research is proposed), how use of hydrogen in firing will impact the quality of the ceramic products, and what the corresponding techno-economic characteristics, like CAPEX and OPEX, of these hydrogen burners would be for the ceramic industry.

[11] Electrolysis of water by renewable electricity (e.g. from solar panels).

4.1.3 Electric heating

Electric heating could potentially fully replace the use of natural gas and related CO_2 emissions in the fire kiln by using renewable electricity as energy input. Furthermore, the extra heat that is required for drying could also be supplied by electric heating. On a smaller scale, this technique is used by pottery bakers. However, the production capacity of these installations cannot be compared to large scale ceramic plants. Electric furnace kilns have not yet been implemented on a large and continuous scale (i.e. in tunnel kilns). The feasibility of applying electric kilns in large scale ceramic production plants therefore remains unproven. In addition, electrification of the furnace will significantly increase the onsite electricity consumption. It is uncertain whether the capacity of the local electricity infrastructure would be able to supply this electricity as ceramic production plants are located typically in more rural areas (Parsons Brinckerhoff & DNVGL, 2015).

The TCKI has performed a simulation in which it compared electric drying with hydrogen and natural gas drying. One of the conclusions of this simulations is that electric drying would be the most energy efficient in terms of amount of air needed, thus resulting in less losses through flue gases. The characteristics of an electric kiln was also simulated for different air inlet temperatures and temperature of heat flows within the kiln, and compared to a reference natural gas fired kiln. The simulation results show that theoretically an electric kiln would be possible, with an electrical power requirement of up to 10 MW, but this will be a huge challenge (TCKI, 2019). In addition, the impact of using electric heating for firing on the ceramic products of large ceramic plants requires further research.

4.1.4 Microwave radiation

Microwave assist technology (MAT), electromagnetic radiation, is a potential technology for heating ceramics to improve energy efficiency and lower CO_2 emissions. This option is applicable to the drying or firing process by transferring microwave energy to the ceramics. The microwaves have different frequencies, of which the working frequencies for microwave materials processing furnaces are 915 MHz to 18 GHz (Singh, Gupta, & Jain, 2015). The difference compared to conventional heating (transferring heat through conduction, convention and radiation) is that electromagnetic heating converts the electromagnetic energy into heat within the centre of the material, on atom level. In other words, heating is performed from the inside of the material instead conventional heating from the outside. The effective heating through microwave radiation depends on the ability of the material to transfer microwave energy into heat, defined by the dielectric loss factor. Resulting from this, three categories of material can be defined (Singh, Gupta, & Jain, 2015):

- Transparent material: microwaves pass without getting absorbed.
- Conductor material: microwaves are reflected and surficial heating is created by plasma formation.
- Absorber material: microwaves are absorbed and the radiation is converted into heat. Such materials are also called: microwave coupled materials.

A drawback of microwave heating is that the heated ceramics need a higher temperature than room temperature when exposed to a microwave field. Therefore, it is considered to be a complementary technology that should still be combined with conventional or electric heating. The need for an elevated temperature has two reasons: firstly, the chemical reactions (e.g. calcination, sintering) of the heated ceramics demands a pre-heated surrounding and secondly, it ensures uniform heating of the ceramics. According to a study of Shulman (2007), this technique is especially suitable for fine grained ceramics and realises a significant decrease in energy use. As visualised in Figure 25, the energy requirements while using MAT is less than 50% of using conventional heating. The main reason for this difference is the duration of the firing process, which is less than two hours for using MAT and nearly five hours for conventional heating.

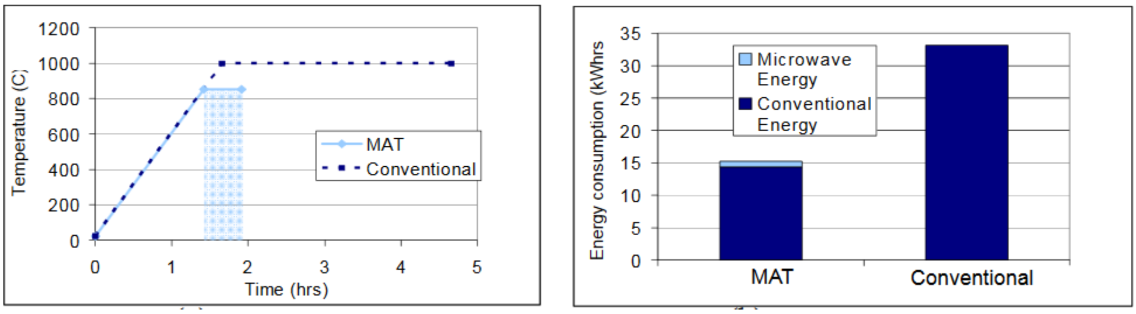


Figure 25. On the left the temperature and duration of the firing process and on the right the total energy consumption. Source: (Shulman, 2007).

This microwave (or infrared) technique could also be combined within an electric kiln, described in 4.1.3, to deliver heat more efficiently to specific high temperature sections of the kiln (Parsons Brinckerhoff & DNVGL, 2015).

A barrier to MAT could be possible risks associated with the microwaves. This might force the plant to change the kiln and dryer design (e.g. adding protecting barriers) and protect its employees from harmful radiation. This new plant design can cause technical and logistic challenges. Lastly, the effects of microwaves on the properties (such as discolouration) of the final ceramic products are not fully researched yet. The TCKI started in 2019 a research to clarify this matter by applying x-ray differentiation on the ceramic products to measure the sensitivity of specific mineral types to microwaves (TCKI, 2019).

4.2 Use of residual energy

This section discusses the decarbonisation options using residual energy for the drying process of ceramics production. An alternative option, which is not related to the heat supply of the ceramics production itself, is the use of residual energy by external parties, such as other companies or in the built environment.

It is important to note that application of drying decarbonisation options is limited by the degree of waste heat that is already used for drying from the firing section. This is because most plants supply a significant part (and sometimes all) of the heat required for drying from the residual heat (of the cooling section) of firing process.

4.2.1 Heat exchange (Heat Matrix)

A significant amount of heat from the firing kiln is lost through hot flue gases (100 – 200 °C), which cannot be ventilated to the drying process due to the corrosive elements present in these flue gases. By using a heat exchanger, the heat could be transferred to clean drying air and used for the drying process. However, a common problem of such heat exchangers is condensation of water that causes deterioration of the steel pipes of the heat exchanger, leading to holes and subsequently mixing of clean environmental air (which will be ventilated to the drying section) with corrosive flue gases (TCKI, 2018).

The Heat Matrix is an innovative heat exchange method that solves this deterioration problem by using plastic pipes (PTFE) and recirculating part of the heated air through the flue gas section. A pilot version of this technology has been tested and validated at Steenfabriek Huissenswaard (Rodruza B.V.) and Steenfabriek Engels Oeffelt in 2017. The outcome of this research was positive and showed that 20 – 25 kW of heat could be captured from the flue gasses (0.7 – 0.9 t/hr). The test setup was 20 to 25 times smaller than a real situation, thus theoretically the heat capture could be 400 – 625 kW (HeatMatrix, 2017). Though this is relatively a small capture (0.144 – 0.225 GJ/t)[12], an advantage of this option is that no other alterations to the manufacturing processes have to be made. The TCKI indicates that this technology is an 'end-of-the-pipe' option, i.e. useful when all other existing energy efficiency improvements have been implemented.

4.2.2 Heat pumps

Industrial closed heat pumps are applicable to the drying process of the ceramic industry. The heat pump allows waste heat to be upgraded to a temperature that is sufficient for drying. Table 6 gives the techno-economic parameters which are adjusted to a heat pump applicable to a ceramic plant with a production capacity of 80 kt/y. The heat pump has an expected lifetime of 12 to 15 years and its variable O&M costs are fully dependent on the electricity price, which is set at 0.053 €/kWh_e for this example (Lensink, 2020, p. 115). The efficiency of the heat pump (expressed as the energy output per electricity consumption, or COP) is assumed to be 3.5 (Lensink, 2020).

Table 6 Parameters for an industrial closed system heat pump Source: adapted from (Lensink, 2020, p. 115).

Parameter	Unit	Value
Heat (output) per year	GJ_{th}	57,600
Investment costs[1]	$M€_{2019}$	2.28
Fixed O&M costs per year	$k€_{2019}/yr$	52
Variable (electricity) O&M costs	$€_{2019}/GJ_{th}$	4.17

[1] Investment costs include the heat pump system, heat exchangers, adapting on-site infrastructure, civil works, disconnecting present heat supply, pumps, engineering costs.

4.2.3 Hybrid drying

The TCKI conducted research to improve the drying process in 2016 and 2017. The improved technology has been named 'Hybridedroger voor keramiek' (hybrid dryer) and has a lower specific energy use and specific CO_2 emission than regular state of the art drying technology (in 2017). The difference with regular drying (in drying chambers or tunnel dryers) is the use of two drying phases (in two drying chambers) instead of only one. First 'aerothermdrogen' (aerothermal drying) is applied, using significant amounts of air, followed by 'semistoomdrogen' (semi-steam drying) which is drying with little air, high temperature and humidity. Aerothermal drying might not be possible during the colder and wetter months of the year, in that case conventional drying should be combined with semi-steam drying (TCKI, 2017). The specific heating requirement lowers from 4-10 GJ/t to approximately 3 GJ/t water that should be evaporated, thus an energy efficiency improvement of 25% to more than 300%. The exact energy improvement for a plant depends on the water content of shaped green ware (ranging from 20 – 30 %) that should be evaporated. The hybrid drying technique makes no or little use of the residual heat from the tunnel kiln, therefore a

[12] Assuming an annual operational time of 8,000 hours and production of 80,000 tonnes. The energy required for drying and firing is both 1.5 GJ/t for brick and roof tile manufacturers (see Figure 14).

condition is that no air is forced through the firing kiln during the cooling down of the wares to ensure a real energy improvement (TCKI, 2017). A way to achieve this might be by combining this technology with an extended tunnel kiln which is further explained in section 4.3.2.

Specific techno-economic information about applying hybrid drying is not available, but costs will come from adjusting the conventional drying chambers (air intake and exhaust, reinforcement and corrosion protection) (TCKI, 2017).

4.3 Process design

The subsections below explain decarbonisation options requiring a different process design. The first option is to extract geothermal energy and apply this in the drying process. The second option is an alteration of the conventional gas-fired kiln, which could also be applied to electric kilns.

4.3.1 Ultra-deep geothermal

Geothermal heat is available from different earth layers below the surface of the Netherlands. Figure 26 shows such layers and the corresponding type of geothermal heat that can be extracted from this layer and deepness. 'Ondiepe geothermie' (shallow geothermal) and 'diepe geothermie' (deep geothermal) do not supply the required heat (i.e. high enough temperature difference). Therefore, only 'ultra diepe geothermie' (ultra-deep geothermal) heat is considered to be applicable to the ceramic industry. The expected temperature that can be achieved by pumping water through such ultra-deep layers is 120 to 140 ^{0}C (Lensink, 2020). The heat can be used in the drying phase of the manufacturing process.

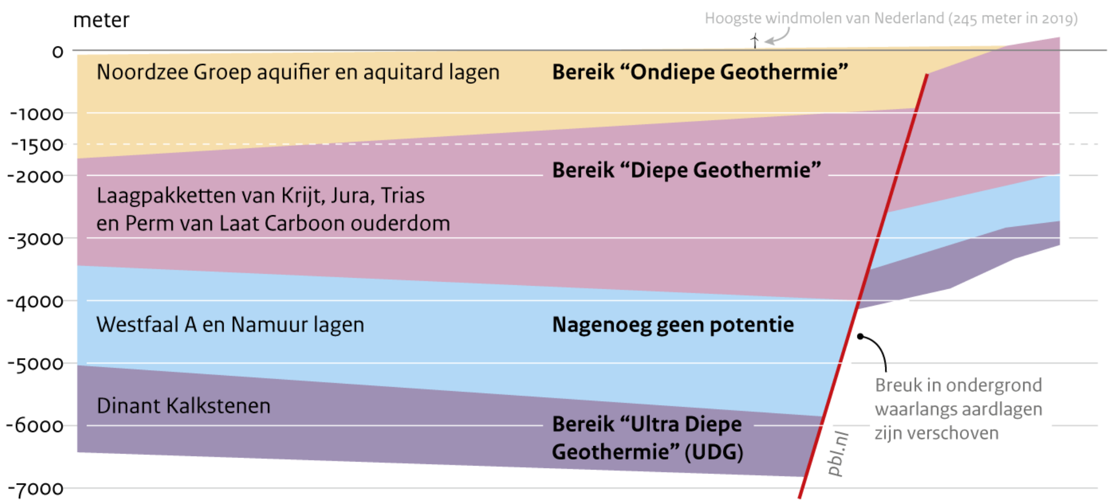


Figure 26. Different earth layers that specify the type of geothermal heat. Source: (Lensink, 2020)

Techno-economic parameters for an ultra-deep geothermal heat installation as described by (Lensink, 2020) are shown in Table 7.

Table 7 Parameters for ultra-deep geothermal. Source: adapted from (Lensink, 2020, p. 70).

Parameter	Unit	Value
Heat (output) per year	GJ	428,400
Investment costs[1]	$M€_{2019}$	42.7
Fixed O&M costs per year[2]	$€_{2019}$/yr	181,900
Variable (electricity) O&M costs	$€_{2019}$/GJ	2.11

[1] Investment costs include drilling costs, pump costs, capture of gas and oil, heat exchangers, above-ground installation, (connection to) heat transport pipeline, geological research.
[2] Fixed O&M costs include warranty and maintenance, grid costs, personnel, administration costs, monitoring system, insurances, spare parts.

4.3.2 Extended tunnel kiln

In 2010, the ceramic sector in the Netherlands initiated the concept of an extended tunnel kiln. This extension is many tens of meters, thus 30 – 50% of the initial tunnel kiln length. This extension allows the bricks to dry without using forced cool air making the tunnel kiln more energy efficient. Another advantage of this concept is that the drying process can be decoupled from the firing kiln, as there is no residual heat from the firing kiln's cooling down section, which is a required condition to apply hybrid drying. A simulation by TCKI shows that gas use lowers from 51 m^3/t to 35 m^3/t (a reduction of 30%) when extending a tunnel kiln with an annual production capacity of approximately 80,000 tonnes (TCKI, 2013; TCKI, 2017).

4.4 CO_2 capture and storage (or utilisation)

Carbon capture and storage (CCS) or utilisation (CCU), can in theory be applied to the ceramic industry. It is assumed that post-combustion capture technology would be applied, where the CO_2 is captured from the flue gases. By capturing CO_2 emissions post-combustion, process emissions are also included in the capture. The capture rate is theoretically possible to be 100%. However, a cost-effective maximum capture rate is set at 90% (IEA, 2017). The captured CO_2 then has to be transported to, for example, the harbour of Rotterdam for storage or utilisation. If transport is not possible through pipelines, then it is transported by truck or ship (which would require liquefaction of the captured CO_2). Especially transport by ship could be an opportunity and should further be researched since many plants are closely located to large rivers.

To give an indication of the cost of CCS, a techno-economic analysis by the International Energy Agency (IEA) of post-combustion CO_2 capture at gas-fired power plants (IEAGHG, 2012) is used, as the CO_2 concentration of the flue gases of both gas fired power plants and ceramic production plants is very low (<5%). The study provides investment and operational cost values (see Table 8). The investment costs consist mostly of the CO_2 capture unit and compressor. The corresponding investment costs per tonne CO_2 are based on a given 25 years lifetime. The energy costs are based on the extra energy consumption that is required for regeneration of the solvent and compression of the carbon dioxide. The operational and variable cost refer to routine maintenance costs and other fixed variable costs (IEAGHG, 2012, p. 102).

Table 8 Parameters for carbon capture at a gas-fired power plant. Source: adapted from (IEAGHG, 2012).

Parameter	Unit	Value
CO_2 capture capacity	Mt/yr	2.5
Investment costs	M€$_{2011}$	602
Fixed OPEX	€$_{2011}$/tCO_2/y	10
Variable OPEX	€$_{2011}$/tCO_2	4
Specific heat consumption	GJ_{th}/tCO_2 captured	3.35
Specific power consumption	GJ_e/tCO_2 captured	0.58

The values in Table 8 represent a capture unit that is far larger than required for a ceramic plant. When considering the relatively small size of the emission volumes per plant, the specific investment costs (EUR/tCO_2 captured/year) are likely to be significantly higher for a carbon capture installation unit at a ceramic plant. Transport and storage costs of CO_2 is an added challenge since many ceramic plants are situated at remote places, without any neighbouring industries that for example could cooperate storing, using or transporting CO_2. Furthermore, CO_2 is (in 2020) only allowed to be stored in in empty natural gas reservoirs in the North Sea and no gas infrastructure for transporting CO_2 is present yet, which means additional costs for shipping or trucks will be added on top of the fee that is to be paid to the facilitator of the storage reservoir[13]. Besides storage, utilisation of captured CO_2 might also be a possibility by supplying CO_2 to greenhouses or to the food and beverage sector.

4.5 Product design

Material reduction by producing 'lighter' products would result in less specific energy consumption during firing (Parsons Brinckerhoff & DNVGL, 2015). Although reducing the amount of CO_2 per function (e.g. square meter wall or pavement), it has to be considered how these changes impact downstream value chain stakeholders, due to changes of the characteristics of the ceramic product.

[13] According to the SDE++ advice, the current prices for transporting and storing CO_2 are 45 €/tCO_2 and 15 €/tCO_2, respectively (Lensink, 2020, p. 141)

5 Discussion

This section discusses the opportunities and barriers for decarbonisation of the ceramic industry.

The ceramic industry has constantly improved its efficiency and reduced its energy use being part of the MJA-agreements for the last 30 years. The remaining carbon dioxide emissions occur mostly during the drying process and the firing process. CO_2 is emitted during these processes by fuel combustion (using natural gas predominantly). During firing, CO_2 emissions are also the result of calcination of carbonates.

Ceramic production involves high temperatures (>1000 °C) and chemical reactions. These characteristics make decarbonisation more challenging, as the options for high temperature processes are limited and because of the sensitiveness of the chemical reactions and their impact on the technical and esthetical characteristics of the end-product.

In the short term, reducing CO_2 emissions of ceramics production could, technically, be achieved by reusing the waste heat from the firing section flue gases for drying using a heat pump, or electric drying. The use of flue gas waste heat for drying using heat exchangers, however, has not been proven on an industrial scale yet. Large scale industrial heat pumps are applied in, among others, the food sector, but have not been proved on an industrial scale at the temperatures required for the drying processes (>100 °C) of the ceramics industry. Electric drying would eliminate on-site emissions from the drying process, but there is no literature about application of this option in the ceramic industry, and therefore its applicability is uncertain. Also, these three options can only reduce a limited amount of carbon dioxide as they do not reduce the process emission or emissions from the firing kiln.

Post-combustion carbon capture and storage (or utilisation) could be applied to capture both the fuel and calcination related emissions, but the CO_2 concentration of ceramic industrial flue gases is very low (<5%). This in combination with the relatively small CO_2 volumes per plant, making the capture equipment very expensive. In addition, due to the ceramic plants being located far from Dutch foreseen CO_2 storage facilities (i.e. empty gas fields in the North Sea), additional costs are incurred for liquefaction of the captured CO_2 and long-distance transport via shipping or trucks.

For firing, many of the identified technologies are not yet commercially available. It is uncertain if any of the technology options (e.g. electric kilns) will become available before 2030 or at least before 2050. Research is currently focusing on assessing the applicability of technologies. Electric kilns are currently researched to determine the impact electric heating has on the quality of the end-product. Hydrogen is an option that is considered, but has the disadvantage that it is at the moment not supplied via the gas grid, and also the impact on the end-product of using hydrogen for firing requires further research. The impact of using hydrogen on the emissions of nitrogen oxides is also subject to research at the moment.

Ultra-deep geothermal and extended tunnel kilns have potential to reduce energy consumption of respectively, drying and firing, but their industrial scale implementation in the ceramic industry requires further research.

The option that requires the least changes to the production process and energy infrastructure is green gas. Although, currently (generally) not available via gas grids, green gas could potentially be produced on-site using digestion or gasification technology, considering the availability of sustainable biomass.

The lack of currently proven and commercially available options could become a major obstacle for the ceramic industry, considering the long lifetimes of plant equipment. Once a new kiln is invested in, it can take 20 to 30 years before the next investment opportunity.

Another important barrier towards decarbonisation is the remote location of most of the ceramic manufacturing plants (rural areas and sometimes close to Natura2000 areas which are protected), with relatively limited installed grid capacity. This results in possible infrastructure capacity problems when applying electrification options like electric firing and drying, or assisted microwave firing and drying. Therefore, the timeframe and costs of increasing the electricity connection capacity has to be included in the decision-making process.

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Appendix A

This appendix describes the approach used to determine the specific material and energy consumption of the different ceramic production processes and the production volumes and capacity of each plant.

Bricks and roof tiles

The total specific energy consumption for natural gas and electricity are determined in the following steps:

1. The CO_2eq process emissions percentage of the total CO_2eq emissions are calculated based on an estimated 6,200 TJ[14] natural gas consumption in 2015 (RVO, 2016) * 56.6 kgCO_2/GJ natural gas (RVO, 2017)/ 477,079 tCO_2 registered EU ETS emissions in 2015 (Dutch emissions authority, 2020). This results in a process emission part of the total CO_2eq emissions of 26%;

2. There is no public information regarding production volumes of Dutch roof tiles plants. The specific CO_2 emission for roof tiles and bricks production is assumed to be the same. The specific CO_2 emission that is fuel related for bricks production is derived from the EU ETS registered emissions of Dutch brick producing plants and the produced volumes of bricks. The sum of the EU ETS registered emissions in 2016 is taken for the companies producing bricks (see Table 2) and multiplied by the emissions percentage caused by combustion of fuels (1-26% = 74%), which gives 295,048 tCO_2. The amount of total produced bricks in 2016 is 1,229 million bricks 'waalformaat' (WF)[15]. When assuming one WF brick weighs 1.84 kg (KNB, 2017), the amount of produced bricks in 2016 is 2,260,017 tonnes. The specific fuel related CO_2 emissions of bricks production are 295,048 tCO_2 / 2,260,017 tonnes = 0.131 tCO_2/t brick;

3. It is assumed the combustion fuel consists solely of natural gas. The specific natural gas consumption of bricks is therefore 0.131 tCO_2/t brick / 0.0566 kgCO_2/GJ = 2.3 GJ/t bricks;

    a. The specific natural gas consumption of the firing section is assumed to be 0.087 m3/brick (Steenfabriek de Rijswaard B.V., 2020). Assuming the bricks are expressed in 'Waalformaat' (WF) with a weight of 1.84 kg/brick WF, and a lower heating value for natural gas of 31.65 MJ/m^3 (RVO, 2020) gives a natural gas consumption 1.5 GJ/t bricks for firing;

    b. The total thermal energy consumption for firing and baking is assumed to be equal (IEE, 2007), meaning the baking has an energy consumption of 1.5 GJ_{th}/t bricks. Based on the total natural gas consumption of 2.3 GJ/t, the natural gas consumption for drying is assumed to be 0.8 GJ/t. The remaining required thermal energy for drying of 0.7 GJ/t is assumed to come from the extracted heat from the firing section.

[14] Note that this includes ceramic plants that are not in the EU ETS. The deviation is considered negligible in accordance with feedback from the Dutch ceramic industry.

[15] The product categorisation of the plants was not confirmed by the companies and therefore it is uncertain if the list of bricks producing companies used to determine the EU ETS CO_2 emissions for 2016 correlate fully with the list of bricks producing companies as defined by the KNB and their production volumes data.

Note that this calculated value does not account for configurations where a CHP, steam boiler, or other drying method is used to supply additional heat to the drying section.

4. The specific electricity production is 0.245 GJ/t based on (EC, 2007). The specific electricity consumption for the crushing, mixing, conveyor belts, fans, pumps, and lighting is unknown. It is assumed half of the electricity is used for preparation and drying, and the other half is used for firing, sorting, and packaging.

The production (for 2016) and capacity of each plant were calculated based on the assumed specific CO_2eq emissions (0.177 tCO_2eq/t brick) and the registered EU ETS CO_2eq emission data for 2016 (Dutch emissions authority, 2020). A range was applied assuming the accuracy of the calculation to be +10% and -10%. The results were rounded to the nearest 5,000 tonne value. The calculated production capacity was only used if there was no production capacity information available from literature sources.

The capacity of each plant was estimated based the higher end of the calculated production range for 2016, assuming this represents 90% of the total production capacity. The values were rounded to the nearest 5,000 tonne value.

Note that due to limited available public data the calculated values may deviate from the actual energy consumption of Dutch ceramic plants. The values should therefore be treated as indicative values.

Floor and wall tiles

The total specific energy consumption for natural gas and electricity were taken from literature (Koninklijke Mosa B.V., 2017). The allocation of the total SEC to the spray drying, drying, and firing is based on the ratio of heat and electricity consumption[16] for these processes in floor and wall tiles production from European averages (EC, 2007).

The production volumes for 2016 of the two tiles producing plants was calculated using literature data (Koninklijke Mosa B.V., 2017).

The process emissions for wall and roof tiles were calculated to be 11.4% and 1.9% respectively. These were calculated based on the difference between the NEa registered CO_2 emissions for 2016 (Dutch emissions authority, 2020) and the calculated CO_2 emissions from natural gas combustion (based on the total produced tiles multiplied with the specific natural gas consumption).

For consistency with the other ceramic products energy and material balances, the calculated annual production is given in ranges. The range is created by assuming the accuracy of the calculation is +10% and -10%.

Note that due to limited available public data the calculated values may deviate from the actual energy consumption of Dutch ceramic plants. The values should therefore be treated as indicative values.

Refractory bricks

For refractory bricks, a specific CO_2 emissions of 0.3225 tCO_2/t brick was used (Ecofys, 2009) to calculate the production volumes of 2015, using the registered CO_2 emissions (Dutch emissions authority, 2020).The process emission percentage of the total emissions was assumed to be 26%; the same as for bricks and roof tiles.

16 The average was taken for ranges in the BREF document.

The natural gas consumption was calculated by subtracting the process emissions from the total specific CO_2 emissions, and using 56.4 $kgCO_2$/GJ as emission factor for natural gas (RVO, 2017). This gives a specific natural gas consumption of 4.35 GJ/t refractory brick. The specific electricity consumption is based on the average of the SEC given by table 3.17 of (EC, 2007), giving 1.295 GJ/t.

It is assumed that natural gas is used only in the process 'Drying, firing'. The specific natural gas consumption and waste heat consumption for drying is assumed to be the same as for normal bricks. The remaining gas consumption is allocated to the firing process. The electricity consumption is assumed to be equally distributed to the 'Preparation, shaping, and drying' and 'Firing, sorting, and packaging'.

Due to the uncertainty of the calculated SECs, annual production values are given in a range. The range is created by assuming the accuracy of the calculation is +10% and -10%.

Note that due to limited available public data the calculated values may deviate from the actual energy consumption of Dutch ceramic plants. The values should therefore be treated as indicative values.