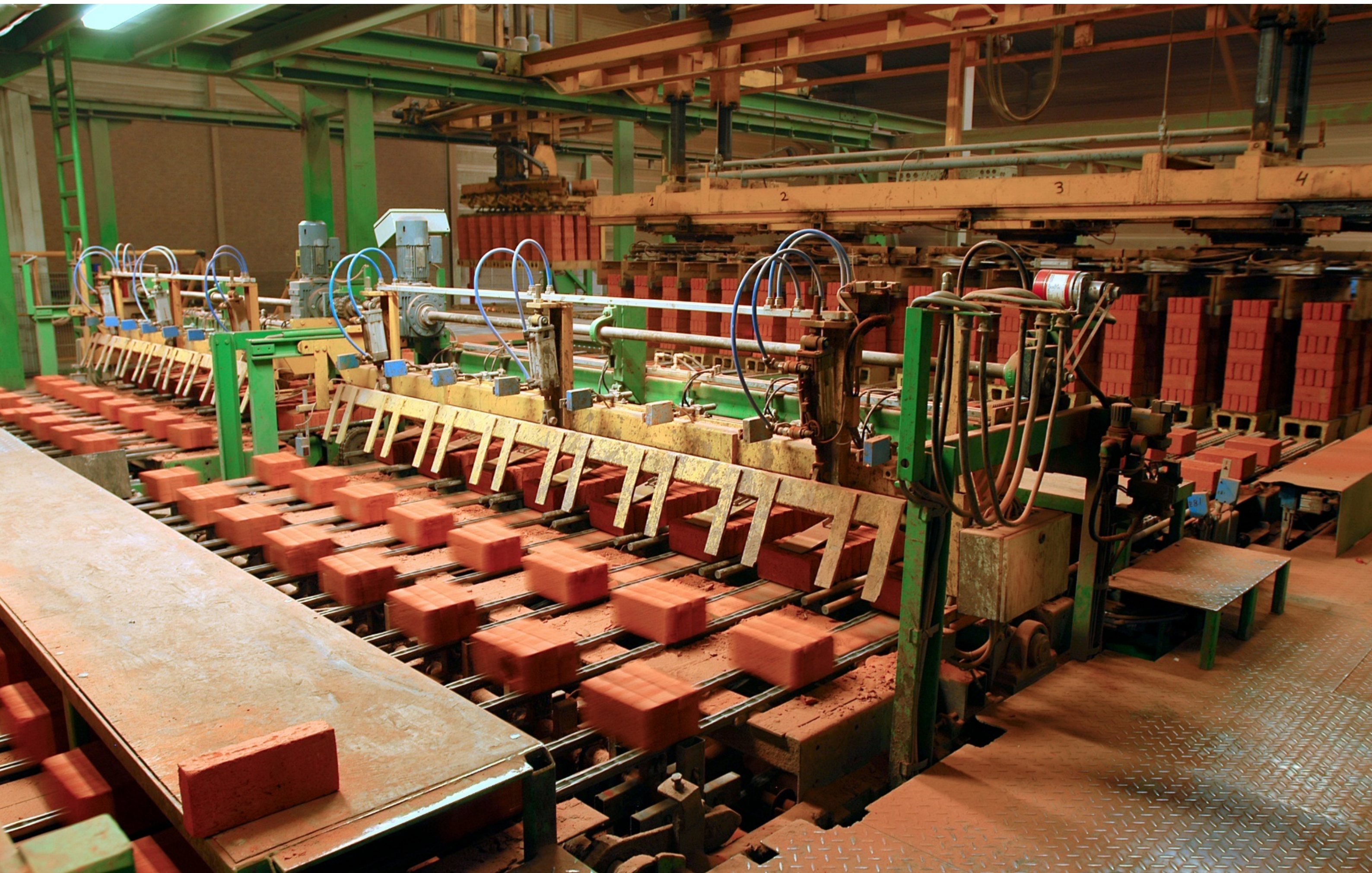
DECARBONISATION OF THE DUTCH CERAMIC INDUSTRY

A TECHNO-ECONOMIC ANALYSIS OF DECARBONISATION OPTIONS

Jorick Besier, MSc thesis



Decarbonisation of the Dutch ceramic industry

A techno-economic analysis of decarbonisation technologies

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **Complex Systems Engineering and Management**

Faculty of Technology, Policy and Management

by

Jorick Besier

Student number: 4974549

To be defended in public on January 13, 2021

Graduation committee

Chairperson	: Prof.dr. K. Blok, Energy & Industry
First Supervisor	: Prof.dr. K. Blok, Energy & Industry
Second Supervisor	: Prof.dr. R.W. Künneke, Economics of Technology and Innovation
External Supervisor	: M. Marsidi, PBL

Executive summary

The Dutch ceramic industry has a long-lasting and successful history due to the big rivers that transport sediments from higher parts of Europe to the Netherlands. Presently, the ceramic industry consists of 43 operational plants, owned by 17 companies. The production processes of the different ceramic products is energy intensive as it requires high temperatures. Such temperatures are reached by burning natural gas, the main source of energy that is used by the ceramic plants and responsible for a major part of the total CO_2 emissions of the ceramic industry. According to the Dutch climate agreement, the ceramic industry should contribute to reducing their CO_2 emissions.

However, it is unclear how the ceramic industry in the Netherlands can decarbonise (i.e. reduce CO_2 emissions of) their production process. No literature is available that describes the production processes and neither is known what technologies or adaptations to the process are applicable for decarbonisation. And lastly, no clear decarbonisation pathway is available to reach the targets of the climate agreement in 2030 and beyond. Therefore, this study intends to provide an overview of the ceramic production processes in the Netherlands and to analyse applicable decarbonisation options towards 2030. The research objective is formulated into a main research question:

"Following a techno-economic perspective, how can the ceramic industry in the Netherlands decarbonise their manufacturing processes?"

The main research question is subdivided in four different sub-questions, listed below and answered chronologically through the research of this thesis. The answers to the sub-questions together enable a comprehensive answer to the main research question.

SQ1: *"What characterises a techno-economic perspective that can be applied on decarbonisation of the ceramic industry?"*

SQ2: *"What is the current state of the ceramic sector in terms of processes and CO_2 emissions?"*

SQ3: *"From a technological perspective, how can the ceramic industry in the Netherlands be decarbonised?"*

SQ4: *"From an economic perspective, how can the ceramic industry in the Netherlands be decarbonised?"*

The first step of research is creating a theoretical framework in which the underlying theories and methods are discussed. The theoretical framework answers *SQ1* by showing that a techno-economic perspective is best applicable to the problem defined in this thesis when following the characteristics of a normative scenario and a bottom-up approach to describe the production processes of the ceramic industry in detail. The applied method for determining the CO_2 emission flows per process step is an input-output analysis which enables the visualisation of the material, energy and CO_2 emissions flows of the ceramic production processes by means of flow diagrams. Furthermore, the theoretical framework discusses the neoclassical economists' view which is dominant in this research and enables the analysis of marginal abatement cost curves and a business case analysis. Limitations of this view and corresponding methods are mentioned in the theoretical framework and will be considered and discussed throughout the analyses.
After defining the theoretical framework, the next step of research is translating this theory into a methodology that is applicable to the decarbonisation of the Dutch ceramic industry. First an overview of the ceramic production processes is created by means of system

analysis and therewith answering *SQ2*. The results of the system analysis show that three product categories can be distinguished in the Netherlands: bricks and roof tiles, floor and wall tiles, and refractory products. Bricks and roof tiles are most dominant, covering the total ceramic production by more than 96%. Furthermore, the results show that the critical process steps emitting CO_2 are identified to be the drying and firing steps.

To analyse decarbonisation pathways for these two critical process steps, decarbonisation options are identified and analysed through desk research and consultation with industry experts. In total, eleven technologies or adaptations are analysed that are applicable to decarbonise one or both of these process steps. Among the options are fuel substitutions (e.g. green gas), residual energy users (e.g. industrial heat pumps), alterations in the process design (e.g. extended tunnel kiln) and the capture of CO_2. For most of the options, techno-economic parameters could be derived, which are important to perform the analysis of the marginal abatement cost curves and the business case analyses.

The results from these two analyses provide answers to both *SQ3* and *SQ4*. Theoretically, a combination of these options could decarbonise the process for more than 90% of which the remaining emissions can all be related to emissions resulting from chemical reactions during the firing process. However, from a technical perspective and therewith answering *SQ3*, some important parameters cannot be defined or have a high uncertainty for decarbonisation options like heat recovery and the extended tunnel kiln. More importantly, from an economic perspective, and therewith answering *SQ4*, only industrial heat pumps turned out to be more cost-effective than the 'business-as-usual' technologies using natural gas. All other options would require substantially higher CO_2 taxes (than the applied 47 €/tCO_2), or subsidies, to become cost-effective in 2030. Furthermore, the sensitivity analyses show that a different electricity price has the biggest impact, which makes this an important factor of the decarbonisation pathways.

The answers of the four sub research questions show little perspective for decarbonisation of the ceramic industry in 2030. By answering the main research question, you may conclude that the ceramic industry in the Netherlands can decarbonise their production process by implementing industrial heat pumps, which will decarbonise the process by 26% but decreases the energy efficiency of the whole process. This decarbonisation percentage could rise to 40% when heat recovery from flue gases and the extended tunnel kiln turn out to be applicable too, however this could not be verified in this research due to missing cost numbers. Considering the CO_2 emissions related to the high temperature firing process, green gas from onsite digestion is the most attractive decarbonisation option based on the technical results, however this option will not be cost-effective and possible barriers exist considering the supply or production of green gas. And last, the process emissions could technically be captured by CCS or CCU, however this is neither economically feasible based on the results of this research, nor it is clear whether transport and storage or utilisation are possible.

Due to several limitations and factors not included in the scope of this research, the following further research is recommended: Apply a socio-technical perspective on the decarbonisation pathways, perform a detailed case study of one or a few ceramic plants, and conduct a more detailed study on process specific decarbonisation options to derive the required technical and economic information that is needed for further analysis.

Contents

1 Introduction

This Master Thesis describes the current situation of ceramic production in the Netherlands and the options and preconditions for its decarbonisation. By applying different decarbonisation options, it analyses the different decarbonisation pathways 2030. The ceramic industry produces solid materials comprising of an inorganic compound of metal or metalloid and non-metal with ionic or covalent bonds. This thesis focuses on the production of ceramic products used in the construction or industry sectors, such as bricks, tiles, and refractory products.

This chapter is ordered in the following way: First section 1.1 gives a brief introduction of the ceramic industry in the Netherlands. Then section 1.2 defines the problem, including knowledge gaps related to this problem. This is followed by section 1.3 which states the research objectives, research questions and scope of this thesis. Section 1.4 describes the research approach. The link with the master programme CoSEM is described in section 1.5. Finally, the outline of this thesis is stated in section 1.6.

1.1 Problem context

Ceramic manufacturing industry 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).

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

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

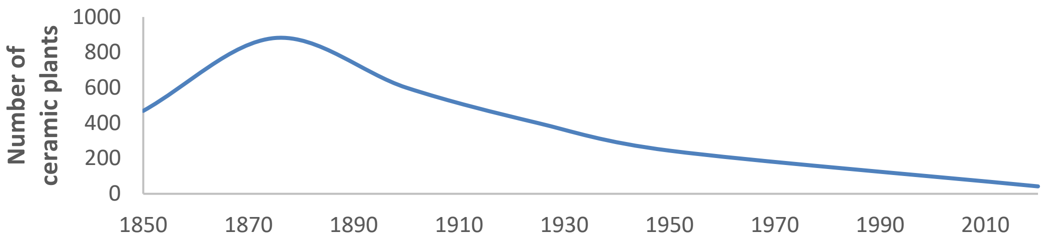


Figure 2. The rise and decline of the number of ceramic plants in the Netherlands over the last two centuries. Source: adapted from Corten (1994).

Today, 43 coarse[1] ceramic plants are operational, owned by 16 companies, which are represented by the Dutch ceramic branch organization (KNB)[2] (KNB, 2020).

Climate agreement

The Dutch climate agreement ('Klimaatakkoord'), which was introduced in 2019, has set a target for 2030 for the Dutch industrial sector to abate its CO_2eq emissions by 19.4 Mt compared to 2015 (Klimaatakkoord, 2019, p. 83). The long-term goal is to reduce the total CO_2eq emissions in the Netherlands by 95% compared to 1990 (Klimaatakkoord, 2019).

The ceramic industry in The Netherlands, representing manufacturers of bricks, tiles and refractory products, is part of the industrial sector and has a total annual CO_2eq emission profile of approximately 500 thousand tonnes[3]. Comparing this emission profile with the total annual emissions of Dutch companies registered at the EU ETS shows that the ceramic industry is responsible for 0.6% in 2019 (see Table 1). It is interesting to note that – in contrast with the CO_2eq emission profile – this percentage has gradually increased over the years 2015 to 2019, from 0.51% to 0.60%. Because the ceramic industry is part of the industrial sector in the Netherlands, it should contribute to the abatement policies stated by the climate agreement. In addition to these targets, gas extraction from the Groningen gas reservoirs is scheduled to be phased out before 2030[4]. 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 (Correljé, Van der Linde, & Westerwoudt, 2003).

Table 1 Total annual CO_2eq emission numbers for the ceramic industry in the Netherlands and percentage of total emissions in the Netherlands (Nea, 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

[1] Coarse ceramics are here defined as ceramics used in the construction sector.
[2] In addition, a plant not represented by the KNB but included in this thesis is Gouda Refractories B.V., manufacturer of refractory products. This plant is not represented by the KNB because it is not a manufacturer of coarse ceramics. Its products are meant for the inner lining of ovens for high temperature processes, such as in the glass or steel industry.
[3] The total CO_2eq emissions of the 37 biggest ceramic plants that are registered at the EU ETS.
[4] A phase out by 2030 is mentioned by GasTerra (Gasterra, 2019)

1.2 Problem statement

The Dutch industrial sector is well aware of the energy intensity of the different industrial processes, such as the ceramic production processes. However, knowledge on a detailed process level is lacking. This is, for example, shown by the Dutch Emission Authority (NEa) and Pollutant Release and Transfer Register (Emissieregistratie), two institutions that monitor the greenhouse gas emissions of all plants operating in the industrial sector[5]. The emission numbers provided by those institutions are only available at plant level and show no information about specific processes. Furthermore, it is not specified whether the CO_2 emissions are the result of chemical reactions or from burning fuel, for example.

Considering the ceramic industry, only brief explanations are given about the manufacturing processes in public sources from the ceramic companies and related research institutes like the Technical Centre for the Ceramic Industry (TCKI). The source that has provided most detailed information about the ceramic manufacturing processes is published by the European Commission: The BAT (Best Available Techniques) Reference Document of the Ceramic Manufacturing Industry (BREF) (EC, 2007). This reference document addresses the industrial activities of all ceramic manufacturers[6] that are located within the European Union. The BREF is structured according to the type of ceramic product and the provided numbers are retrieved from empirical research and technical working groups. Nevertheless, the provided numbers are not complete in this BREF, especially regarding CO_2 emissions. And mainly due to the fact that the reference document covers the whole ceramic industry in the European Union, it is difficult for individual parties to determine what alternatives and related factors are applicable to them (Ibáñez-Forés, Bovea, & Azapagic, 2013). Finally, validation in the reference document with data specifically from the Dutch ceramic industry is missing.

Any recently published academic literature of the Dutch ceramic industry is neither available. The only public information that can be retrieved are websites and reports, most of which are related to a ceramic plant, the branch organisation KNB, or research institute TCKI.

Altogether, this results in the first knowledge gap resulting from the problem statement, as little knowledge of the manufacturing processes in the Netherlands is available, and related to this the specific CO_2 emissions[7] for each of the products and their process steps.

Knowledge gap 1: Lack of detailed knowledge of specific manufacturing processes of the Dutch ceramic industry, and related product and process specific CO_2 emissions.

Besides the detailed knowledge of the ceramic manufacturing processes in the Netherlands, the best options to decarbonise such specific processes are neither mentioned in literature. For the last decades energy efficiency improvements have been realised in the ceramic sector, accelerated by the 'Meerjarenafspraken' (MJA-agreements), resulting in more efficient manufacturing processes (RVO, 2020). However, these changes resulting from MJA-agreements do not (fully) focus on CO_2 reduction and are therefore not expected to be sufficient enough to meet the objectives of the Dutch climate agreement. This also becomes

[5] A minimum level of activity is required for being monitored. For example, ceramic plants require a minimum production capacity of 75 tonnes per day. Source: (Nea, 2020).
[6] With a production capacity exceeding 75 tonnes per day, and/or with a kiln capacity exceeding 4 m^3 and with a setting density per kiln exceeding 300 kg/m^3 (EC, 2007).
[7] Specific CO_2 emission is the amount of tonne CO_2 per tonne end product.

clear from the BREF document, which lists a number of techniques and technologies of which none are intended specifically for reducing CO_2 emissions (EC, 2007).

Only a small number of academic papers are written about the decarbonisation potentials and pathways (and relevant decarbonisation options) of ceramic manufacturing processes, which all focus on tiles manufacturing. For example, the paper by Monfort, et al. (2010) analyses different processes of ceramic tiles plants in Spain. Another paper studies CO_2 reduction options for ceramic tiles plants in China (Peng, Zhao, Jiao, Zheng, & Zeng, 2012). And last, Ibn-Mohammed, et al. (2019) concentrates only on the decarbonisation options for a specific process step (i.e. sintering) and does not specify whether this process step is applicable to the manufacturing process of all ceramic products. Characteristics such as specific CO_2 emissions in those studies differ from each other, which shows among other things that the ceramic industries of two different countries cannot be easily compared or used as input for the problem introduced in this thesis. Moreover, the most produced product within the Netherlands is bricks and not ceramic tiles (KNB, 2018).

Therefore, a second knowledge gap can be formulated as a result from lack of information about decarbonisation options that can theoretically be applied to the Dutch ceramic production processes. This knowledge gap is especially relevant considering the unknown specific CO_2 emissions of the different decarbonisation options.

Knowledge gap 2: Lack of detailed information of decarbonisation options that suitable for the Dutch ceramic manufacturing processes.

Finally, the shift from the current ceramic production process to a more sustainable production process with less CO_2 emissions would not be immediately possible, due to the long lifetime of equipment (e.g. firing kilns) used in the plants and decarbonisation options that are undeveloped or not yet commercially available (Cerame Unie, 2012). Therefore, decarbonisation pathways are required to enable an analysis of implementation of decarbonisation options. Decarbonisation pathways can be constructed to determine these parameters and are based on policies and economic/technical trends. This is stated by Maier, et al. (2016) as being different assumptions about the future. Such scenarios give a clear overview for decision-makers, by overcoming the false certainty of only one forecast and providing a range of future possibilities (Roxburgh, 2009).

Considering the published literature that references to the ceramic industry in the Netherlands, only a roadmap to 2030 has become available without detailed or validated results (KNB, 2020). Therefore, the third knowledge gap can be formulated due to the absence of any decarbonisation pathways for the ceramic industry in the Netherlands.

Knowledge gap 3: No decarbonisation pathways available for the ceramic industry in the Netherlands.

1.3 Research objective

This thesis intents to fill the knowledge gaps discussed in the former section and therewith to provide a clear and detailed overview of the ceramic production process, including an analysis of different decarbonisation pathways to and from the year 2030. This specific year is chosen because it is an important year considering the targets of the Dutch climate agreement (Klimaatakkoord, 2019). The added value of this research will be in terms of better decision-making tools for both sides of the field, thus being helpful to policy makers who need to implement the criteria of the climate agreement and the owners of ceramic plants that want to continue their business in the ceramic sector. From the perspective of the owners of the ceramic plants, i.e. a business perspective, the objective of this thesis is to provide guidance to implementing the right decarbonisation options. In other words, it helps determining when a business case could be available to decarbonise their production process.

Obtained insights of this research will be used by the Netherlands Environmental Assessment Agency (PBL) and ECN, part of TNO, as input for a knowledge base for decarbonising the whole industrial sector of the Netherlands[8].

1.3.1 Research questions

From the stated knowledge gaps and described research objective, it can be concluded that the decarbonisation of the different Dutch ceramic manufacturing processes plays a central role in this thesis and that both technical and economic aspects are present. The technical aspect is the required mitigation of CO_2 emissions and the economic aspect is the cost-effectiveness of the decarbonisation options that could result into a business case. In the theoretical framework (see section 2.1) such a techno-economic perspective is further discussed. Taking this all into account, the main research question is formulated as follows.

"Following a techno-economic perspective, how can the ceramic industry in the Netherlands decarbonise their manufacturing processes?"

This main research question is subdivided in four different sub-questions (*SQ1, SQ2, SQ3* and *SQ4*), which are listed below. The formulation of these sub-questions is briefly described for each sub-question below, and further elaborated in section 1.4.

The first sub-question provides an answer to the first part of the main research question, which will be an explanation of the techno-economic perspective and corresponding characteristics when applied on the ceramic industry in the Netherlands. Therefore the following first sub research question is formulated.

SQ1: "What characterises a techno-economic perspective that can be applied on decarbonisation of the ceramic industry?"

It becomes clear from the problem statement that little information is present about the ceramic industry in the Netherlands and the detailed characteristics of its different production processes. Directly related to this, the specific CO_2 emissions are also unknown. Resulting from this, the second sub research question is formulated as follows.

[8] This thesis will contribute to the Manufacturing Industry Decarbonisation Data Exchange Network (MIDDEN). See for more information: https://www.pbl.nl/en/middenweb.

SQ2: "What is the current state of the ceramic sector in terms of processes and CO_2 emissions?"

The third and fourth sub research questions are again focused on the techno-economic perspective. To get a complete picture of the possibilities of decarbonisation, the technological and economic aspects are independently approached by the third and fourth sub research question, respectively. Accordingly, the following sub research questions are formulated.

SQ3: From a technological perspective, how can the ceramic industry in the Netherlands be decarbonised?

SQ4: "From an economic perspective, how can the ceramic industry in the Netherlands be decarbonised?

1.3.2 Research scope

The scope of this thesis includes all ceramic plants in the Netherlands that are member of the KNB, and Gouda Refractories, which is not represented by the KNB[9]. Considering the process characteristics, only the processes are analysed that take place within the walls of the ceramic plants. This means that, for example, the CO_2 emissions that result from transporting finished products (e.g. by trucks) to warehouses is not in the scope of this thesis. Considering the decarbonisation options, the availability of required feedstock and the deposition of possible rest material is within the scope of analysis in this research. Finally, there is no limit to time, though the focus is on the year starting in 2030.

1.4 Research approach

From the brief introduction of the ceramic industry and the related problem statement, a research approach is determined to answer the main research question and its sub research questions. These sub-questions are answered following a theoretical and methodological approach. In this thesis is chosen for an exploratory approach, which is preferred when very little knowledge or information is available on the subject that is being researched (Sekaran & Bougie, 2016). The exploratory approach is chosen for this thesis because there is no clear overview of specific data (e.g. CO_2 emissions) of the ceramic production processes and no available decarbonisation pathways. Therefore, it will be analysed in an explorative way to what extent specific decarbonisation options are applicable to the ceramic production processes and what the effect of implementing these options will be on the decrease of CO_2 emissions.

The subsections below explain more into detail how each of the four sub research questions are approached and sufficiently be answered in the remainder of this thesis. After answering all sub research questions and deriving the relevant results, the main research question can be answered.

Providing a knowledge base

The exploratory approach begins by conducting a literature review to create a theoretical framework which provides a knowledge base for the research in this thesis. The different types of scenarios, scenario models, and the perspectives on energy transition (and more

[9] All ceramic plants that are part of the EU ETS list (in total 37) are within this scope.

specific on decarbonisation) are further elaborated in the theoretical framework (see section 2.1). The type of scenario analysis that is followed in this thesis implies the formation of a hypothetical situation, starting in the year 2030, in which new technologies (or alterations in existing technologies) are adapted for and implemented in the ceramic production processes. For the years after 2030, no changes occur in those implemented decarbonisation options while in operation. Other input parameters, such as energy prices and taxes, for example, are also be determined for the year 2030, and a sensitivity analysis will be conducted to measure their impact on the results. This is further elaborated in the methodology (see section 3.1). Altogether, this first step of the approach will provide an answer to *SQ1*.

Empirical research

The input for the analysis from a techno-economic perspective is mainly derived from empirical research, following a bottom-up approach (see section 3.2). The empirical research is performed to provide a detailed overview of the manufacturing processes and corresponding mass, energy and CO_2 emission flows. Along with other information derived from the ceramic industry (e.g. annual production numbers), and experts consultation, this empirical research results in an overview the current state of the Dutch ceramic industry and therefore answers *SQ2*. Furthermore, this empirical research provides a first step in answering *SQ3* and *SQ4* by creating an overview of the applicable decarbonisation options.

Marginal abatement cost curves

From the overview of the current processes of the ceramic industry, which results from the empirical research, critical process steps can be determined. Process steps are specified as critical in this thesis when their output flows consists of CO_2 emissions. These critical process steps must be decarbonised by specific decarbonisation options. As further discussed in the theoretical framework (see section 2.4), a regional assessment of mitigation technologies is preferred. Therefore the economic potential of these technologies to abate CO_2 emissions can be determined by a bottom-up approach, as already mentioned above, followed by ordering the potential decarbonisation options according to their cost per reduced tonne CO_2 [€/tCO_2] (van Vuuren, et al., 2009). This is called the marginal abatement cost (MAC). When this economic order of potential decarbonisation costs is combined with the cumulative abatement potential of these options, a MAC curve figure can be constructed. The applications of MACs in research and corresponding limitations are further discussed in the theoretical framework (see section 2.4). The methodology (see section 3.3) will further elaborate on the methods and equations of constructing MAC curves for the Dutch ceramic industry, and will discuss the methods' limitations. Altogether, it provides an answer to the *SQ3* and takes an important step into answering *SQ4*.

Business case analysis

To determine what decarbonisation options should be implemented from a business perspective, and therewith answering *SQ4*, the decarbonisation options should be analysed from the view of the plant owners. The added value of applying this approach is to provide a realistic point of view on decarbonisation for the ceramic plant owners. Such analysis is referred to in this thesis as business case analysis (BCA), which is a decision support and planning tool to project the results and consequences of an action or a decision. The analysis provides answers in terms of business costs, business benefits and business risks (Schmidt, 2018), and is further discussed in the theoretical framework (see section 2.5). The added value of this BCA is that extra factors are included such as risks and benefits, which are neglected when assessing the cost-effectiveness from a social perspective (see subsection 3.3.1).

1.5 Link with Master programme

The master Complex Systems Engineering and Management (CoSEM) requires a multidisciplinary research approach that considers technical, institutional, economic and social knowledge. This thesis answers to this requirement by combining the construction of a technical energy system environment with institutional and economic analyses. Methods, tools and techniques are used that assess the impact of technical solutions (i.e. decarbonisation options) on organisations with a system engineering approach, but also by including decision-making tools for effective management strategies. The academic contribution of this thesis can be given in terms of innovative analysis of decarbonisation technologies and a detailed overview of the Dutch ceramic production process characteristics which could be used for further analysis. The subsections below elaborate further on the academic contribution in terms of scientific and societal relevance.

Scientific relevance

This thesis provides insight into the scientific field in several ways. First it contributes to the general scientific literature that concentrates on decarbonisation pathways with attributed characteristics and methods. Second, methods are used and discussed that enable a technical and economic analysis of decarbonisation options for the ceramic industry. The methods and results of this analysis could be used for a broader field than only the ceramic sector, since nearly all decarbonisation options are applicable to industries with similar characteristics as the ceramic industry in the Netherlands. The underlying theory and relevant methods are further discussed in the theoretical framework in chapter 2.

Societal relevance

The societal relevance of this thesis is provided by the acquired knowledge on decarbonisation pathways. This attributes to the governance and decision-making process of preparing ceramic plants for a fossil-free world, by evaluating different decarbonisation pathways from a social and private perspective. This is especially relevant to governmental structures, both in the Netherlands and neighbouring countries with similar ceramic industries, to acquire more knowledge of possible decarbonisation pathways. The societal relevance could also be described by the contribution of the empirical research in this thesis to the MIDDEN project, which will collect all information in the MIDDEN database. This database provides a publicly available overview of detailed data of the current situation and a future timeline, including the decarbonisation options. The database consists of the ceramic general plant data (e.g. name, address, and energy requirements), specific process step details, technology characteristics and product details (e.g. market price).

1.6 Outline of thesis

The remainder of this thesis will be as follows. First, chapter 2 provides the theoretical framework of the terms and approaches stated in the subsection above and answers *SQ1* in the conclusion of the theoretical framework (see section 2.6). Second, chapter 3 provides the methodology of this thesis which elaborates on the methods and tools (e.g. empirical research, MAC, BCA) that are used for this research. Third, the system of interest is described in chapter 4, which outlines the ceramic industry in the Netherlands and applicable decarbonisation options. In the conclusion of this chapter *SQ2* is answered. These results are visualised and discussed in chapter 5. The concluding section of the results will answer *SQ3* and *SQ4*. Finally, the results are discussed in chapter 6 and concluded by answering the main research question in the conclusion in chapter 7.

2 Theoretical framework

This chapter discusses the theoretical literature underlying the introduced terms and approaches in the introduction. The reviewed literature provides a theoretical framework which acts as a supporting structure of the analysis in this thesis.

The chapter is structured as follows. First, section 2.1 elaborates on the different types of scenarios and models that have been applied on energy related problems through the years. From this overview, a description follows of different perspectives on decarbonisation, which ends by providing an answer to the *SQ1*: *"What characterises a techno-economic perspective that can be applied on decarbonisation of the ceramic industry?"* Second, section 2.2 describes how energy systems are analysed by different literature. Following from this, it is discussed how the system can be described of the different ceramic manufacturing processes and related energy, material and emission flows. Third, section 2.2 discusses the economic part of the main research question of this thesis. Different economic approaches are discussed on their description of the economic aspects of the ceramic manufacturing processes and decarbonisation of these processes. Fourth, section 2.4 provides an overview of the marginal abatement cost curves and section 2.5 elaborates on the cost benefit analysis, which approaches the problem more from the side of the ceramic plant owners. Finally, section 2.6 concludes on the theoretical framework and answers the first sub research question, on which the methodology in the next chapter is based.

2.1 Perspectives on energy transition

The development and planning of policies based on climate targets are discussed broadly in literature. Considering the determination of specific sector CO_2 reduction potentials, a detailed description of the whole energy system is required, and related socio-economic factors, to generate sufficient results (Boonekamp, 2006). Associated with this discussion is the choice of scenario models and applications. The contribution of such scenario models and applications is explained by Amer, Daim & Jetter (2013) as stimulating strategic thinking and overcoming the limitations of multiple futures. This improves decision making process and identification of new issues and problems which may arise in the future (Varum & Melo, 2010). The first successful application of scenario models in the energy (and private) sector has been achieved by Shell, which made them able to deal with unexpected high prices during the oil crisis in 1973 (Wack, 1985). Since then, scenario models have become more widely used and are further developed in the last decades.

Before further discussing the specific use and type of models, different types of scenarios can be distinguished. Those have been summarised by Börjeson, et al., (2006) in three main categories with corresponding questions between the parentheses: predictive scenarios ("What will happen?"), explorative scenarios ("What can happen?") and normative scenarios ("How can a specific target be reached?"). The normative scenario is used by several studies on CO_2 mitigation. For example, (Simon, Naegler, & Gils, 2018) state that normative scenarios should be preferred over explorative scenarios, because normative scenarios enable a better understanding of transformation potentials of the researched system. Such normative scenarios are employed to visualise what is possible instead of being a prognosis (Simon, Naegler, & Gils, 2018). In contrast to the advantages of applying normative scenarios, another paper states that there could be significant input uncertainties and output discrepancies, even when using accurate simulation tools (Dascalaki, Balaras, Kontoyiannidis, & Droutsa, 2016).

Considering the different scenario models relevant to energy transitions, Kiregler, et al. (2015) states that integrated assessment models (IAMs) are applicable to balance the costs and benefits under uncertainty, which requires a combination of climate models with global economic models. This is also mentioned by van Vuuren, et al. (2011) who state that a combination two types of models should be used: climate models and IAMs. Climate modellers will concentrate on the future concentrations and emissions of greenhouse gases and air pollutants. Simultaneously, modellers that follow the approach of IAMs will concentrate on different technological, socio-economic and policy aspects. Combining these two types of models allows for developing representative concentration pathways (Moss, et al., 2010). An example of such a study is given by Fortes, Alvarenga, Seixas & Rodrigues (2015) who combine socio-economic storylines with energy modelling for long-term energy scenarios in Portugal. An important result of their study is that the cost-effective criteria of the future energy technologies (i.e. decarbonisation options) do not match the expectations of national stakeholders. This difference is caused by the energy models being fully rational and the actors having different perspectives on energy transitions.

The use of different perspectives is also mentioned by Cherp, et al. (2018), who state that three perspectives on national energy transitions can be distinguished: a techno-economic perspective, a socio-technical perspective and a political perspective. Each of these perspectives has its own systemic focus and corresponding limitations (see Table 2).

Table 2 Three perspectives on energy transitions. Source: adapted from Cherp, et al. (2018).

Perspective	Systemic focus	Examples of models and applications	Limitations
Techno-economic	Energy flows and markets	IAMs[1] and long-term climate-energy scenarios	Poor representation of technology inertia, innovation, and policy change
Socio-technical	Energy technologies embedded in socio-technical systems	Transition management, innovation policies	Excessive focus on novelty, strive for "seamless web"
Political	Political actions and energy policies	Design of international regimes and domestic policies	Poor representation of material factors

[1]IAM stands for integrated assessment model.

The first perspective is a techno-economic perspective, already briefly introduced in subsection 1.3.1, which has IAMS and long-term clime-energy scenarios as examples of models and applications (see Table 2). This techno-economic perspective uses a supply-demand balance of the energy flows which can be seen in conjunction with the neoclassical economic approach (see section 2.2 for an overview of the economic approaches). The techno-economic perspective can be applied through IAMs to estimate the costs of climate stabilisation policies (which is related to the research objective of this thesis) (Clarke & Jiang, 2014). However, Edelenbosch, et al. (2017) argue that IAMs do not have a scope that is detailed enough for determining specific CO_2 reduction technologies because IAMs often assess the industry in an aggregated manner. Such estimates of short and long-term energy and CO_2 reduction potentials, and other related characteristics, are very important to know for the evaluation of decarbonisation strategies and development of industry specific policies (Kermeli, et al., 2019). A similar statement is made by Weitzel (2017) who stresses that regional assessment of mitigation technologies are needed because global averages can hide important consequences.

Furthermore, it is relevant whether the reference levels should follow a frozen technology and/or frozen efficiency level. This is explained by Blok & Nieuwlaar (2017) as a hypothetical situation without any change in energy technologies, neither at the supply nor the demand side. A frozen efficiency level is similar to the frozen technology level in terms of the efficiency remaining constant over the time period of analysis. The efficiency value is set at the base year, i.e. the start of the analysis, which would be 2030 considering this thesis (see section 1.3). Several studies that assessed CO_2 reduction options in industry have followed a frozen-technology reference level (e.g. Kuramochi (2016), Variny (2020)). Using those frozen technology and efficiency levels is a simplified representation of reality because it normally can be assumed that efficiency improves over time and that new technologies could be adopted during the time period of the scenario planning. When such autonomous technology changes are included, the reference level is referred to as business-as-usual. Despite the business-as-usual level having more relevant results, the frozen technology and efficiency levels are an important starting point in analyses, especially when bottom-up approaches are applied (Blok & Nieuwlaar, 2017).

2.2 System analysis

The analysis of an energy systems, which are the different ceramic production processes in this thesis, is generally based on the combination of top-down and bottom-up information gathering (Blok & Nieuwlaar, 2017). The top-down information is about the entity or industry as a whole, whereas bottom-up information is about the individual equipment. The difference between both methods is explained by Bohringer & Rutherford (2008) as the emphasis on market adjustments for macro-economic top-down approaches and the emphasis on energy technologies for technologic bottom-up approaches. A similar statement is made by van Vuuren, et al. (2009), according to whom a typical bottom-up approach focuses on the individual technologies and not on the relationship with the whole system (i.e. the whole economy). A limitation of the bottom-up approach is that there is little macro-economic feedback between the other (e.g. industrial) sectors or inclusion of the economic impacts of climate and energy policies, which could result in limited representation of reality (van Vuuren, et al., 2009).

Studies with similar research objectives and approaches to this study made use of an initial top-down approach to create a general overview, followed by extensive bottom-up research to analyse the energy, material and emissions flows (Altenburg, 2020; Papadogeorgos, 2019; Keys, 2019). According to Blok & Nieuwlaar (2017), in general the following procedure is followed for an energy analysis, which will enable the construction of a process scheme:

- Determining the total energy use;
- Creating an overview of all energy users (e.g. technologies);
- Creating an overview of system characteristics (e.g. production rate);
- Perform additional measurements to get more complete or accurate information;
- Closing the energy balance (see equation 3.2 and 3.3 in section 3.2)

The above bullet points can also be applied to create an overview of the material balances, including the CO_2 emissions flows. Because the emphasis of this thesis is on the CO_2 emission flows, i.e. the environmental impact of the ceramic production processes, a number of methods is available to assess this impact. Examples of such methods are the environmental impact assessment, system of economic and environmental accounting, environmental auditing, life-cycle assessment, material flow analysis, and input-output analysis (Wrisberg, Udo de Haes, Triebswetter, Eder, & Clift, 2002; Finnveden & Moberg, 2005). The type of tool determines the scope of analysis and is based on certain characteristics, such as the need for an analytical or procedural tool, or whether (macro-) economic impacts should also be considered next to environmental impacts. From the list of tools described above, the input-output analysis is considered most suitable to creating an overview of the ceramic production processes because it provides a clear overview of the CO_2 emissions per technology that is used.

The input-output analysis was originally designed for economic systems, and assumed to be in balance or equilibrium such that total inputs add up to the total outputs (Tan, Aviso, Promentilla, Yu, & Santos, 2019). The input-output analysis became later also useful for the analysis of a local industrial supply chains, which could be industrial processes like the ceramic production process (Albino, Izzo, & Kühtz, 2002). The interactions between such local industrial supply chains, by Blok & Nieuwlaar (2017) referred to as a process scheme, transform predefined inputs into outputs and waste and/or emissions (see Figure 3).

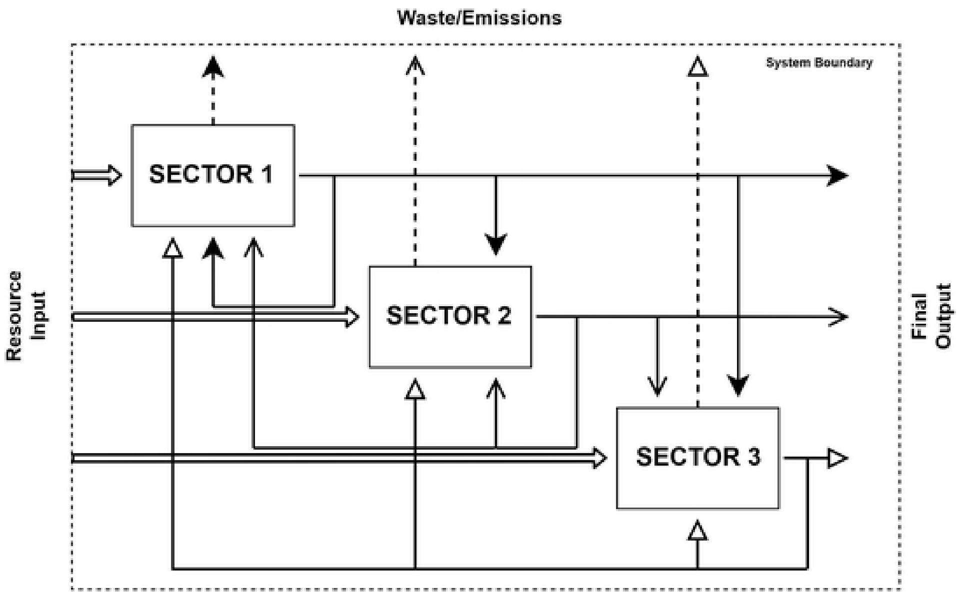


Figure 3. Conceptual framework of an input-output system. Source: (Tan, Aviso, Promentilla, Yu, & Santos, 2019)

The input-output system has several assumptions, which could be limiting the quality of research. Most important assumption is the absence of a supply constraint. In other words, it assumed that material, feedstock and energy supply are infinitely available. Furthermore, the input of each process step is fixed and exactly the same process steps should be followed for similar products (Tan, Aviso, Promentilla, Yu, & Santos, 2019). Taking these limitations into account, the input-output system would be applicable to analysing the system of the different ceramic manufacturing processes. From a technical perspective, this analysis provides the results that are required for analysing the decarbonisation options for the ceramic industry in the Netherlands. Section 3.2 will further explain on the specific methods and tools applied in the research of this thesis.

2.3 Economic approaches

The mainstream school of economics, as defined by Correljé & Groenewegen (2009), has been the neoclassical economics and new institutional economics. The neoclassical economics is based on transparency (i.e. known prices that reflect scarcity) and flexibility of market parties as its main principles. This traditional view relies on an unseen hand of the market which coordinates the prices, markets, demand and supply, and efficiency. In the end, this mechanism ensures that the most efficient solution or price is taken that maximises welfare (Hazeu, 2007). Furthermore, it assumes that all actors behave rationally and that no incomplete or asymmetric information is present. The field of neoclassical economics has been extended since the last 30 years by adding several game theories, which in the end all aim for the most efficient solution and can therefore be added to this view (Groenewegen, 2004).

The neoclassical approach has several limitations, which are described by Hazeu (2007). First, it does not provide any guidance to other ways of cooperation, when not being performed through market mechanisms. Another limitation is the focus of on the uniform goal of maximisation, for example, of profit. And it does not provide answers to multiform goals. Furthermore, it cannot always be ensured that information is complete. In fact, many situations exist in which incomplete information or uncertainty should be dealt with. An example of such situations is the energy transition, for which it is difficult to acquire complete information and a degree of certainty for the future, due to the complexity of the system and assumptions that are required (Geels, Schwanen, Sorrell, Jenkins, & Sovacool, 2018). The neoclassical approach is limited in providing answers to such problems with a long time frame due to its focus on short term optimisation. Finally, another limitation of the neoclassical approach is the neglecting of heterogeneous goods and search costs.

Because of these limitations of the neoclassical approach, it became necessary to get more insight in the influence of the institutions (i.e. rules and laws) that were part of the economic processes and allocations. This has resulted in another economic approach, which was named the institutional economics. An important addition to this institutional economics approach compared to the neoclassical approach was the definition of transaction costs. Such transaction costs are the result of transferring ownership of the goods between actors. Hazeu (2007) has subdivided transactions (i.e. transferring ownership) in three types: market transactions, internal transactions and political transactions. By including those transactions and their corresponding costs in the economic analysis, it has become clear that not only economic scarcity determines whether transactions take place, but also the related institutions. And therefore, it is not only important to keep the production costs as low as possible, but also the transaction costs.

The new institutional economics approach, which has emerged from the institutional economics approach, defines that actors are bounded in their reality and therefore have opportunistic behaviour (Correljé & Groenewegen, 2009). This opportunistic behaviour requires actors to defend themselves to others' opportunistic behaviour by, for example, creating safeguards and monitoring activity of competitors. Such actions all add up to the transaction costs. The differences between institutions and the approach of neoclassical economics and the new institutional economics is explained by a framework published by Williamson (1998). This framework distinguishes four levels of social analysis with each of the levels having a different time period in which the institutions change. The fourth level of the framework is related to the neoclassical economics approach, in which the institutions change continuously because resources are constantly allocated to minimise production costs (Correljé & Groenewegen, 2009). This level is explained by Williamson (1998) as a marginal analysis with continuous adjustments in price and output. Considering this fourth level of the framework, Correljé & Groenewegen (2009) state that – according to the mainstream economists – only in exceptional cases of market failures governmental intervention can be justified. Market failures can be caused by the presence of public goods (such as dykes to prevent flooding), natural monopolies and the problem of externalities.

The last cause of market failures, externalities, can be related to the energy transition and the CO_2 emissions that should be prevented but cannot be related to any costs figures. And resulting from such an externality, governmental intervention could be in the form of CO_2 taxes. Rogers et al. (1998) has created a framework that shows the concept of externalities, which is adapted from Correljé & Groenewegen (2009) to make it suitable to an analysis of energy provision (see Figure 4). On the left site of the framework, costs are given in several components, and on the right side of the framework the value is given. The transactions take place at the equilibrium price and from a neoclassical economic view the externalities are initially neglected. These externalities are distinguished in economic externalities and intangible externalities (with costs not explicit to decision makers). Correljé & van der Linden (2006) give an example for the second type of externalities with respect to the oil and gas market: they state that such intangible externalities can be related to the costs of civil wars over resource control, or strategic stocks for maintaining security of supply.

Relating the externalities to the energy transition, and more specifically, to the decarbonisation of the Dutch ceramic industry, someone could define the externalities in terms of CO_2 emissions and following from this the health impacts on society. Comparing the additional system costs of reducing CO_2 emissions with the values of lower impact on health shows that the reduced external effects amount to two to six times the additional costs. And it is also argued that the health co-benefits are much higher than associated policy costs (Markandya, et al., 2018; Vandyck, et al., 2018). From a neoclassical economics point of view, such policy costs can be implemented by economic instruments like subsidising or taxing the producer's side (Correljé & Groenewegen, 2009). The methodology further discusses how such instruments are applied in the research of this thesis (see section 3.3).

<table>
<tr><th colspan="4">Costs</th><th rowspan="9">Transaction costs</th><th colspan="3">Values</th></tr>
<tr><td rowspan="2">Intangible Externalities</td><td colspan="2" rowspan="2"></td><td rowspan="8">Full Cost</td><td>Intrinsic value of global environment</td><td rowspan="2"></td><td rowspan="8">Full Value</td></tr>
<tr><td>Value of local environment</td></tr>
<tr><td rowspan="2">Economic Externalities</td><td rowspan="2"></td><td rowspan="6">Full Economic Costs</td><td>Value of social stability</td><td rowspan="6">Full Economic Value</td></tr>
<tr><td>Value of indirect effects</td></tr>
<tr><td>Opportunity Cost</td><td>= Price</td><td rowspan="4">Value to consumers = Price</td></tr>
<tr><td>Capital Charges</td><td rowspan="3">Full supply Cost</td></tr>
<tr><td>Maintenance Cost</td></tr>
<tr><td>Operation Cost</td></tr>
</table>

Figure 4. A framework that explains the concept of externalities. Source: (Correljé & Groenewegen, 2009)

2.4 Marginal abatement cost curves

The first application of MAC curves dates back to the beginning of the 1980s, when a cost curve for the reduction in electricity consumption was constructed (Meier, 1982). At this time, such a curve was called a savings curve or conservation supply curve. In the years that followed by the publication of Meier (1982), several abatement curves were constructed for other purposes than CO_2 abatement, such as the abatement of air pollution or the reduction of waste. The first assessment of CO_2 abatement was published in the beginning of the 1990s and since then a significant amount of research have been applied on it.

For example, McKinsey & Company has been developing a global greenhouse gas (GHG) abatement database since 2006. Three years later, this resulted in an overview of global MAC curves for the different sectors (e.g. agricultural sector) that show the abatement potential in 2030 (see Figure 5). According to this report, the MAC results could serve as starting point when discussing how best to achieve emission reductions (Nauclér & Enkvist, 2009). The opportunities for reduction are subdivided in three categories: energy efficiency, low carbon energy supply and terrestrial carbon. Nonetheless, Nauclér & Enkvist (2009) state two critical notes of using this method because several factors are neglected. First, transaction costs are excluded from the MAC calculations. As discussed in the former section, these transaction costs are all the costs occurring besides the technical project costs[10]. An example of such transaction costs are implementation costs (e.g. training programs. Next to the transaction costs, institutional costs and non-monetary costs (i.e. intangible externalities (see Figure 4)) are excluded (Vogt-Schilb & Hallegatte, 2014). The second critical note of Nauclér & Enkvist (2009) is that behavioural changes are not included in the MAC analysis. Behavioural changes can be driven by price and non-price factors. Examples of such factors are awareness campaigns or policy changes.

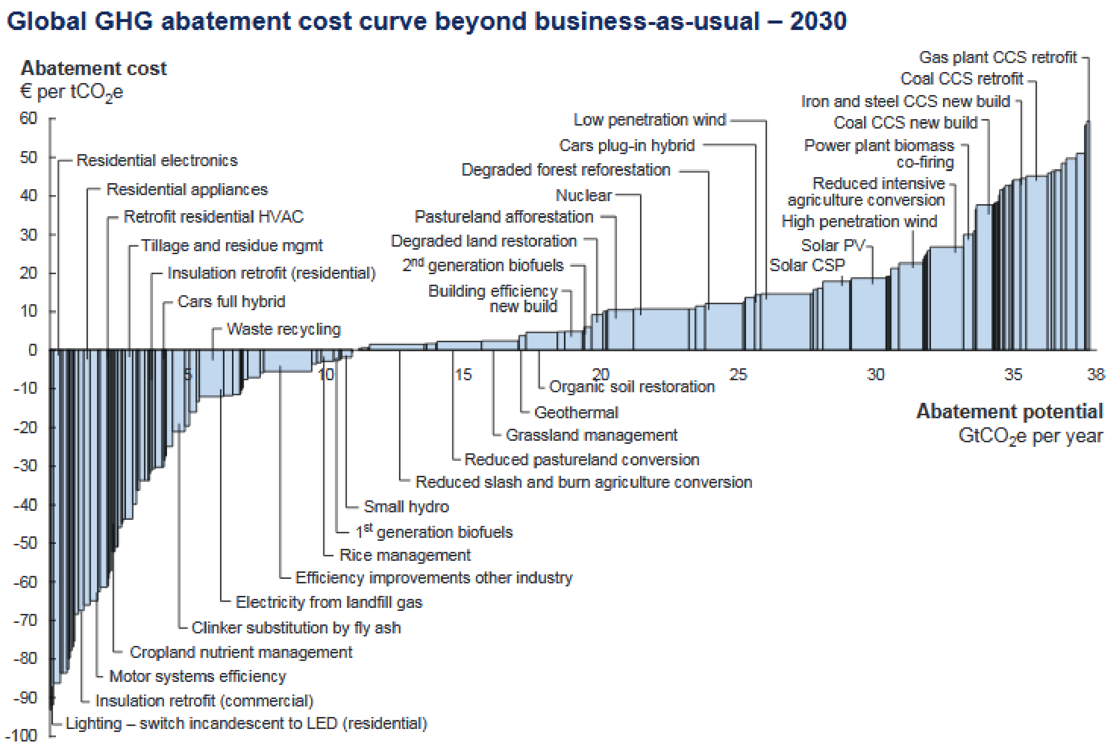


Figure 5. MAC curve for the global emissions of GHG. Source: (Nauclér & Enkvist, 2009).

[10] The technical project costs is often referred to as production costs.

In addition to the critical notes stated by the authors, Kesicki & Ekins (2012) have published a paper in which they discuss the McKinsey & Company report. The first relevant and critical note they state is that the numbers on which the MAC curves are based should be robust. This robustness can be achieved by the quality of assumptions and the method that is conducted to calculate the cost numbers. Especially regarding the assumptions, Kesicki & Ekins (2012) emphasise that all assumptions should be clearly defined and further explained if necessary. Furthermore, Kesicki & Ekins argue that a sensitivity analysis should be conducted to show the impact of changing input assumptions. MAC curves have two other limitations that have are not discussed above. First, the cost and performance of technologies are assumed to be fixed. As a result intertemporal dynamics are excluded, which could become one the biggest barriers to conducting MAC curves when using long time periods (Kesicki & Ekins, 2012). The outcome of this fixed cost and performance is that the MAC curve is to some extent directly dependent on the implementation characteristics of the different decarbonisation options. Second, there might be competition between two or more decarbonisation options. This competitive aspect is not included in the MAC curve (Blok & Nieuwlaar, 2017).

Examples of studies that constructed MAC curves for the analysis of decarbonisation options applicable to the ceramic industry are Ibáñez-Forés, et al., (2013) and Ibn-Mohammed, et al., (2019), who follow a techno-economic approach (see section 2.1) and calculate the cumulative abatement potential to derive a MAC curve. In addition to the cumulative abatement potential, the MAC curve could be used to determine the average cost and total abatement cost by calculating the integral (Kesicki & Strachan, 2011). Furthermore, Kesicki & Strachan (2011) explain that two approaches for deriving MAC curves can be distinguished. A MAC curve based on the individual assessment of abatement measures and a MAC curve resulting from a system approach with an energy model that runs many times.

Discount rate

An important aspect of assessing MACs is the discount rate (Kesicki & Strachan, 2011). Discount rates are used to compare costs of different time periods. A higher discount rate, for example, would put more weight on the initial costs (e.g. investment) compared to the costs and financial benefits that occur later in the timeframe. The discount rate can be approached from two perspectives: the social (or government) perspective and the private (or business) perspective. The main difference between the two perspectives is the time preference, which results in social discounts rate that generally are much lower than private discount rates by business investors (Blok & Nieuwlaar, 2017). This is also stated by Kesicki & Ekins (2012), who conclude that a social discount rate might provide some guidance to the reader, but gives no clear answer to what the market would do. The applicability and value of both discount rates is further discussed in the methodology (see section 3.3).

Other parameters for MAC calculations

When a techno-economic approach is applied (see section 2.1), the systemic focus should be on energy flows and markets (Cherp, et al., 2018). Therefore, techno-economic parameters are required to provide an overview of the decarbonisation options. Such techno-economic parameters have been applied in literature that conducted similar research as the research applied in this thesis. For example, Horvath, et al. (2018) and Chiuta, et al. (2016) include in their analysis the total investment cost (CAPEX), which is a summation of capital costs of all components. Besides the CAPEX, the operation expenditures (OPEX) is also used by Chiuta, et al. (2016) as a combination of operation and maintenance costs, feedstock costs and by-product revenue. Furthermore, Horvath, et al. (2018) and Chiuta, et al. (2016) state that the OPEX could reduce compared to CAPEX as a result of technical learning. Finally, the capital recovery rate, which is a result of the applied discount rate and expected lifetime of the technology, is mentioned by literature and Blok & Nieuwlaar (2017).

2.5 Cost benefit analysis

The MAC curves provide a clear overview of possible decarbonisation technologies that can be a solution to the problem of decarbonising the ceramic production process. However, the impact on the businesses of the ceramic plants in not assessed by MAC curves. In fact, only the marginal costs (or benefits with negative costs) are economic results of MAC analysis. Therefore, another analysis is required which predicts the impact on businesses and gives a clear economic perspective on the decarbonisation options. This analysis could be the cost benefit analysis, which is referred to in this thesis as BCA. The BCA has been widely used for many purposes and applications, for example in project appraisals, project evaluations and as informational studies (Mechler, 2016). A risk of applying BCA is that everything should be monetized and aggregated to the present time, whereas this is sometimes a too simplified representation of reality. This limitation is also stated by (Hansjürgens, 2004), who explains that BCA is part of the neoclassical economics views and further stresses the problem of future uncertainty, irreversibility, and a unknown discount rate for long-term timeframes.

Nevertheless, considering analysis of renewable energy and decarbonisation technologies, with uncertain feasibility of the project, BCA has been used in different studies and is a suitable for such evaluations (Mathioulakis, Panaras, & Belessiotis, 2013). An opportunity of BCA is that it is flexible enough to be applied from any type of scenario, including the normative scenario (Boardman, Greenberg, Vining, & Weimer, 2012). BCA generates in monetary terms an evaluation whether to change to a new product or technology, guiding decision-makers (e.g. ceramic plant owners) to make the most efficient allocation of resources (Boardman, Greenberg, Vining, & Weimer, 2012; Bolderdijk & Steg, 2015).

For most evaluation parameters of BCA, it is important to aggregate costs and benefits in a similar timeframe, which means that future values need to discounted to their present value (IRENA, 2015). Therefore, to perform a cost benefit analysis of decarbonisation options for the ceramic industry in the Netherlands, a private discount rate should be used because this discount rate includes the risks and benefits of the investors. This private discount rate is based on the weighted average cost of capital (WACC) of the market party, representing the required returns from both depth and equity (Kuckshinrichs & Koj, 2018). However, a disadvantage of using this private discount rate is that it is often unknown, since economic factors such as the ratio between depth and equity, and their required returns, are considered a trade secret by most market parties (Krupa & Harvey, 2017). Furthermore, empirical data shows that large differences in private discount rates exist between countries and even within countries significant differences exist (Steffen, 2020). Another limitation of the BCA is that this analysis only covers the economic feasibility of a certain product or technology. Lastly, environmental costs (which could result from CO_2 emissions) are not part of the decision-making process of the market parties and therefore have no impact on the private discount rate (Kuckshinrichs & Koj, 2018).

Evaluation parameters for BCA

Several parameters can be used to perform a BCA. A future situation is analysed, thus a bounded rationality is present because not all information is known. From this follows opportunistic behaviour, which follows from a neoclassical economics approach and results in the use of benchmarks. It can never be known whether one of these benchmarks is the best solution (Hazeu, 2007). Nevertheless, such benchmarks will be used in this thesis to determine which decarbonisation options are most cost-effective.

Such parameters are the net present value (NPV), profit margin, levelized cost of energy, internal rate of return (IRR) and the payback period (PBP) (Blok & Nieuwlaar, 2017; Freixas & Rochet, 1999). The parameters that are assessed in this thesis are further discussed in the methodology (see section 3.4).

2.6 Concluding on the theoretical framework

This chapter has provided an overview of the theory that will underline the research of this thesis. Furthermore, it provides an answer to *SQ1* which is as follows.

"What characterises a techno-economic perspective that can be applied on decarbonisation of the ceramic industry?"

This sub research question can be answered by means of applying a specific type of scenario thinking, which results in several possible approaches and perspectives. Considering the scenario types, three main categories are discussed in the first section: predictive, explorative and normative scenarios. The normative scenario is considered most applicable to the ceramic industry because normative scenarios enable the best understanding of transformations of systems that must be decarbonised.

This goal of decarbonisation is further discussed in section 2.1 which provides three different perspectives on decarbonisation: a techno-economic perspective, a socio-technical perspective and a political perspective. Each of these perspectives has a particular scope which enables a different approach to the problem and the use of different types of scenario models. From the discussed literature, it follows that a techno-economic perspective is best applicable to the problem defined in this thesis. Moreover, the main focus should be on a bottom-up approach to describe the ceramic manufacturing processes (which is also discussed in section 2.2) and relevant decarbonisation options. However, limitations of this approach are presents in the form of no feedback between systems of other industries and no inclusion of policies. An example of such policies for the ceramic industry is the economic tax on CO_2 emissions (which is further discussed in section 2.3).

Section 2.2 discusses the system analysis of the ceramic manufacturing processes, which can be seen as local supply chains. Therefore the specific material, energy and CO_2 emissions can be visualised by means of an input-output analysis. However, a number of assumptions are required for this analysis, such as assuming that the supply of feedstock and energy is infinitely available. This cannot be simply guaranteed and should therefore be discussed while analysing the results of the input-output analysis. Furthermore, it is discussed that the focus should be on a bottom-up approach, however, limitations of this approach are presents by lack of feedback between other industries' systems and no inclusion of policies. An example of such policies could be an economic tax on CO_2 emissions.

Besides these mostly technical aspects of analysing the ceramic manufacturing processes, section 2.3 describes the economic views and approaches that should be followed. The most important difference between a neoclassical and institutional economics view is the inclusion of transaction costs and related institutions in an institutional economics view. Such transaction costs and institutions are not defined by neoclassical. The economic view most suitable to the research approach of this thesis is the neoclassical economist view. Nevertheless, it should be discussed that economic and intangible externalities are initially neglected and should therefore be included by governmental policy instruments.

Finally, section 2.4 discusses the MAC analysis, and section 2.5 describes the BCA. Both the MAC analysis and BCA are best suited to be approached from a neoclassical economist's point of view. The MAC analysis results in a clear graphical visualisation of the decarbonisation options' cost-effectiveness, and the BCA provides several evaluation parameters. Important points of attention for applying MAC analysis and BCA on the Dutch ceramic industry are the determination of correct discount rates, possible competitiveness from other (similar) industries or between technologies, and intertemporal dynamics.

3 Methodology

This chapter elaborates on the different methods and tools that are applied in the research of this thesis. No sub research questions will be answered by this chapter. The starting point (section 3.1) provides an overview, called the methodological framework in this thesis, to show which and in what order methods and tools are applied in the analysis of decarbonising the ceramic industry. Furthermore, a general description and discussion of the input parameters is given. The first section is followed by section 3.2, which is an overview of the empirical research to perform the system analysis, and a description of the reviews by knowledge institutes and industry experts consultation. Then section 3.3 provides a detailed description of the applied methodology for MAC analysis and MAC curves. Last, the method and evaluation parameters of BCA are discussed in section 3.4.

3.1 Methodological framework

From the theoretical discussion in section 2.1, it follows that a normative scenario[11] in combination with a techno-economic perspective is considered to be best applicable to the abatement need of CO_2 emissions resulting from the Dutch ceramic production processes. These scenario type and perspective are chosen to enable the process of questioning and analysis how a specific (fossil-free) future can be realised in terms of energy flows, technologies and cost-effectiveness of the implemented technologies.

Figure 6 shows that the methodological framework states at the top "normative scenario", which covers all methodological steps that are explained in detail later in this chapter. In other words, the applied methods follow the aim of a normative scenario which is reaching an objective that lies in the future. The starting point of this analysis is determining the reference levels, such as starting year and technology and/or efficiency changes. The research of this thesis has a reference year 2030[12] and follows a frozen-technology and frozen-efficiency reference level for the ceramic industry after implementation of the decarbonisation options. These frozen levels imply that no changes occur in energy technologies and their efficiencies (Blok & Nieuwlaar, 2017). In addition, the production growth of the ceramic plants is assumed to be zero per cent. This is based on the annual production numbers, supplied by the KNB, which remained relatively constant over the last few years (KNB, 2018). Therefore, it is assumed that the characteristics of the ceramic industry today, are applicable for the reference year 2030. Furthermore, it follows from the theoretical framework that a bottom-up approach is best applicable (see section 2.1), since the analysis concentrates on the level of energy systems and saving options[13]. Nevertheless, an initial is top-down approach is also applied, as discussed by Blok & Nieuwlaar (2017), to create a general overview of the plants and the ceramic products those plants produce.

Different research steps are stated in Figure 6 that start with a conceptualisation of the ceramic industry (i.e. analysing the system, see section 3.2) and end with the MAC analysis and BCA (see section 3.3 and 3.4. for a detailed description). Following from the conceptualisation of the ceramic industry, Figure 6 shows that critical process steps are determined. Process steps are referred to as critical in this thesis when they haveCO_2 as output emission flow. Based on these critical process steps, relevant decarbonisation options

[11] Please note that the analysis in this thesis is rather a static analysis than a scenario analysis. Nevertheless, the approach of a normative scenario is followed in this thesis.
[12] Referred to in the research approach as starting year (see section 1.4).
[13] In this thesis the emphasis is on CO_2 reduction options (which could be the result of energy savings).

are derived and analysed with an emphasis on techno-economic characteristics like CAPEX, OPEX, lifetime and the CO_2 abatement (see section 3.3). This created overview of decarbonisation options that can theoretically be implemented in the ceramic production processes provides the input for the analysis of these decarbonisation options. Part of this analysis is the computation of MACs and construction of MAC curves, both from a social and private perspective. The difference between the social and private perspective is that the private perspective uses a higher discount rate (see subsection 3.3.1) and the economic externality of a CO_2 tax policy is included. This tax is directly related to the CO_2 price [€/tCO_2], which is shown in Figure 4. Last, the methodological framework shows a connection from the block "MAC curve from a private perspective" to the block "Business case analysis". This link results from the fact that a BCA only should be applied if the decarbonisation option is cost-effective, which is visualised by the MAC curve from a private perspective. The methodology of BCA is further discussed in section 3.4, including the net present value (NPV), pay-back period (PBP) and internal rate of return (IRR).

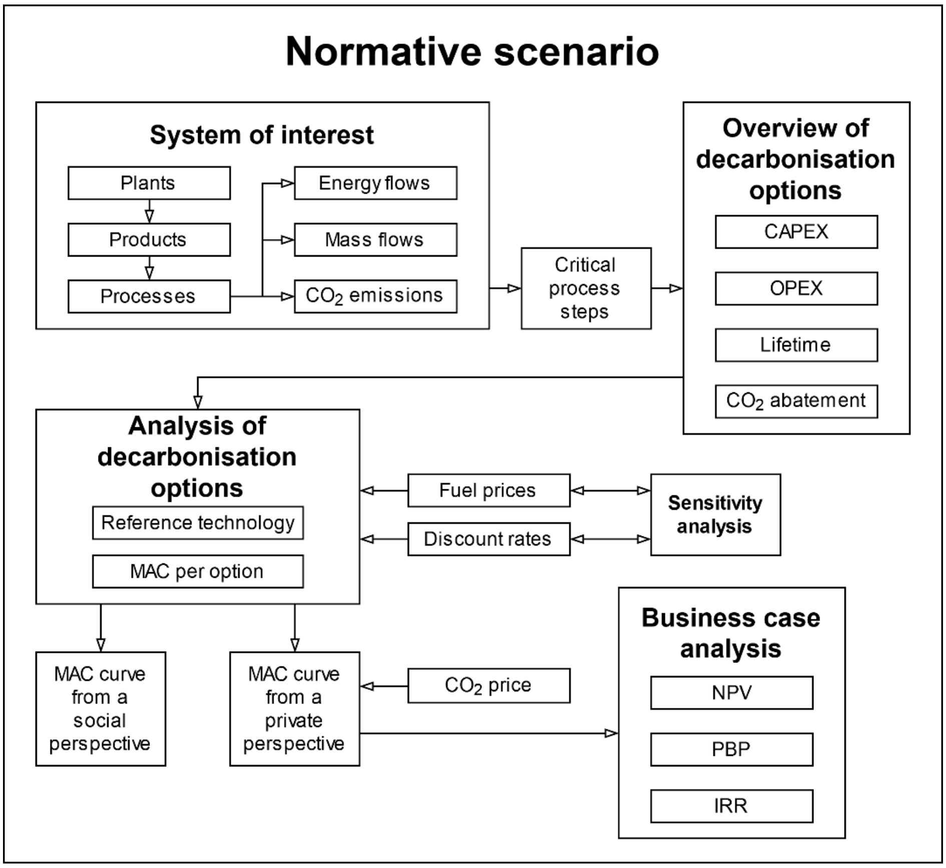


Figure 6. Methodological framework of the methods and tools applied in this research.

Three blocks from the framework in Figure 4 have not yet been mentioned. These blocks are "Fuel prices" and "Discount rates", which are both connected to the block "Sensitivity analysis". Additionally, these two blocks are connected to the bigger block "Analysis of decarbonisation options". The reason for adding these blocks in the framework is to emphasise the application of a sensitivity analysis on the most uncertain input parameters of the MAC analysis and BCA. The sensitivity analysis will eliminate any input uncertainties, which is one of the major limitations of MAC curves, as stated by Kesicki & Ekins (2012). This is further elaborated in the subsections that discuss the MAC and BCA in this chapter.

3.2 System analysis

The system analysis will be conducted by thorough desk research and consultation with plant owners[14] and experts from the ceramic industry to obtain an overview of the relevant companies, their plants and products, and finally the manufacturing processes. The manufacturing processes are analysed by subdividing the process in different process steps, which allows the computation of flows between these process steps by applying the input-output analysis. According to Blok & Nieuwlaar (2017), these flows can be calculated by applying mass and energy balances. Such analysis is also performed by similar studies on decarbonisation (Altenburg, 2020; Papadogeorgos, 2019; Keys, 2019).

Mass and energy balances

The mass and energy flows are partially derived from literature from publicly available sources, scientific literature and other material provided by the ceramic industry. If certain numbers are not available, mass and energy balances are used to calculate the mass and energy flows between ceramic production processes. These balances are based on the law of conservation of mass and energy (Blok & Nieuwlaar, 2017). The law of conservation of mass describes that no mass can be created nor destroyed, given by the following equation:

$$\sum \varphi_{x,in} = \sum \varphi_{x,out} \qquad (3.1)$$

Where $\varphi_{x,in}$ [t] is the mass of streams entering the process step and $\varphi_{x,out}$ [t] is the mass of streams exiting the process step. For the energy balance two equations are given. First the law of conservation of energy and second the equation that describes the energy flow.

$$Q_{in} = Q_{out} + Q_{losses} \qquad (3.2)$$

Where Q_{in} [GJ] is the energy input of the process step, Q_{out} [GJ] the energy coming out of the process and Q_{losses} [GJ] the losses that occur during the process step.

$$Q_j = \varphi_j \cdot c_{pj} \cdot (T_j - T_0) \qquad (3.3)$$

Where Q_j [GJ] is the energy flow calculated from multiplying the mass flow φ_j [t] with its specific heat c_{pj} [GJ/°C/t] and temperature difference $(T_j - T_0)$ [°C]. The results of these calculations are applied in the input-output analysis, with mass, energy and CO_2 flows between boxes that represent the different processes.

Review by knowledge institutes and experts

Several members from knowledge institutes and experts from the ceramic industry have reviewed the obtained empirical results and the performed calculations. First, a report has been written for the MIDDEN project that is led by both PBL and ECN, part of TNO. The MIDDEN report has a considerable overlap with this thesis with the empirical research that results in a system description and overview of decarbonisation options. Throughout the process of writing this thesis has been presented to and discussed with the MIDDEN team[15]. Second, the empirical results have been reviewed by Durk Smink who represents the ceramic branch organisation KNB. Third, the results have been presented to the KNB 'working group environment and energy' consisting of several experts (including Durk Smink) of KNB and executives of Dutch ceramic plants. This meeting resulted in a short validation of energy and material flows for the specific process steps and insights were obtained considering the implementation of (future) decarbonisation options.

---

[14] Unfortunately, due to the COVID-19 situation in the Netherlands, no ceramic plants could be visited to perform a detailed case study. Therefore, only little information could directly be retrieved from plant owners.
[15] All members of the MIDDEN team: https://www.pbl.nl/en/middenweb/project-team-members.

3.3 Overview and analysis of decarbonisation options

The critical process steps that follow from the system analysis enable the determination of suitable decarbonisation options. Those decarbonisation option do not necessarily have to be fully developed and commercial today (i.e. in 2020). Especially when long-term options are studied, which is the case in this thesis with a starting year in 2030, ones that become commercial in 5 to 20 years should also be considered, according to Blok & Nieuwlaar (2017). Therefore, such options are included in this thesis and for each decarbonisation options its state of development is provided. The subsection below describe the applied discount rates and other input parameters, and state the calculation steps of MACs.

3.3.1 Social and private perspectives

Figure 6 shows that the decarbonisation options are used to construct a MAC curve from a social and private perspective. The difference between this social and private perspective is caused by the difference between a social discount rate and private discount rate. The choice of an appropriate discount rate is discussed in literature (e.g. Campos, et al. (2016)), because a discount rate that is too high might be a barrier to socially desirable investments, while a discount rate too low could result in economically inefficient investments (Kuckshinrichs & Koj, 2018). Considering the social discount rate, it results from literature that most often a social discount rate of 3.5% is applied (Moore, Boardman, Vining, Weimer, & Greenberg, 2004; Treasury, H. M. S., 2014). On the other hand, Blok & Nieuwlaar (2017) describe a social discount range of 4 to 6 per cent (for industrialised countries). Taking these statements into consideration, a discount rate of 4% is used in this thesis and, additionally, a sensitivity analysis will be applied to measure the effect of changing this parameter.

The private perspective applies a different and higher discount rate. The exact value of the private discount rate is, similar to the social discount rate, different for most cases. In academic literature, a distinction is made between taking into consideration the varying cost of capital for different parts of the world or only concentrating on one or similar countries (Ondraczek, Komendantova, & Patt, 2015). Since the analysis in this thesis concentrates on the ceramic industry in the Netherlands, the private discount rate will be based on the latter case. An example of such a specific private discount rate is stated by Peters, et al. (2011), who take 8% as a private discount rate for the countries Germany, the USA and Spain. Another report focuses more on a specific industry in the Netherlands, namely the paper and cardboard industry for which a private discount rate of 9% is taken (Ecofys, 2006). Another example is the SDE++ advice, which states a private discount rate ranging from 4 to 6 percent. In this thesis a private discount rate of 9% is used, but since it is unsure whether this discount rate is correct, a sensitivity analysis will be conducted to measure the impact of changing the discount rate.

3.3.2 Input parameters for the MAC calculation

For each of the decarbonisation options, a similar calculation method is applied to determine the MACs and other parameters relevant for the BCA. The input parameters and calculation steps for the marginal abatement cost are visualised in Figure 7 to provide a clear overview of the process of calculating the MACs in this thesis. An important part of this calculation is covered by comparing the decarbonisation options with the reference technology. The reference technology is the technology that is fully or partly replaced by the decarbonisation option. The MAC is based on the extra cost or savings of this replacement. If no reference technology needs to be replaced, the parameters of the decarbonisation option will directly provide input for the MAC calculation. Besides this comparison, external variables (such as the fuel prices, discount rate and CO_2 tax) affect the variable OPEX, capital recovery factor or directly the MAC. Below Figure 7, the input parameters are explained in detail.

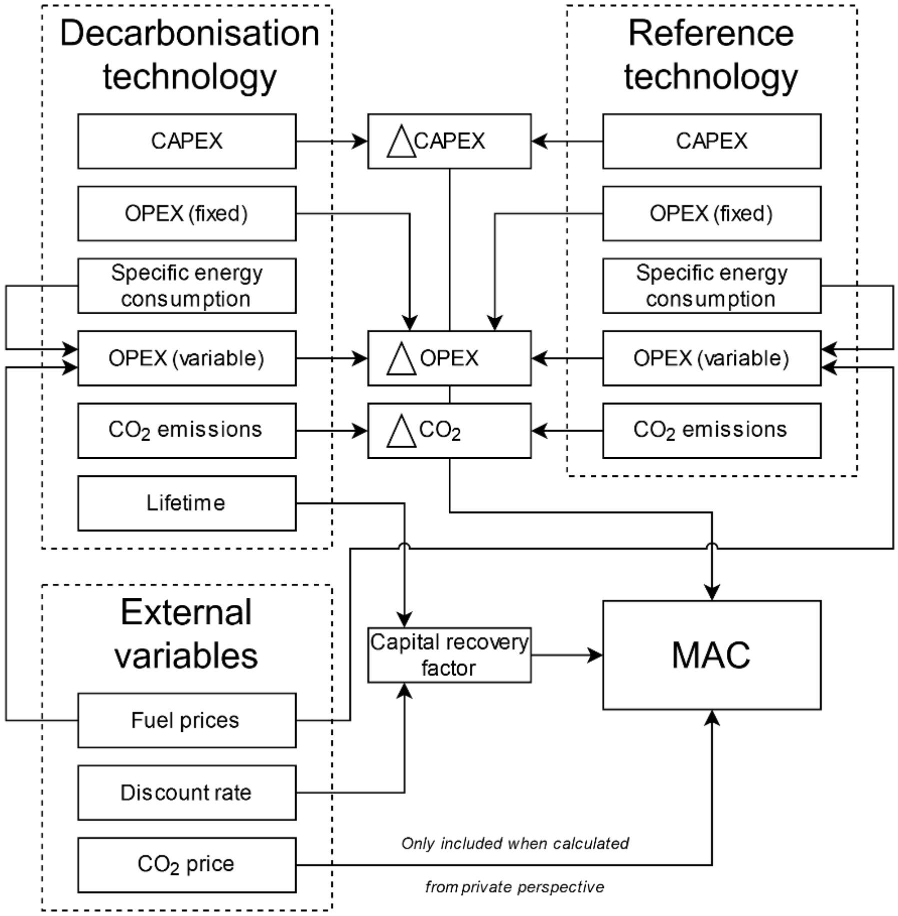


Figure 7. Calculation overview for determining the MAC.

CAPEX
The difference in CAPEX is calculated by subtracting the CAPEX (also referred to as investment costs) of the reference technology from the CAPEX of the decarbonisation option. This difference in CAPEX is only significant to options that physically change the manufacturing process. For example, a possible fuel substitution has no effect on the system and equipment of process step and results therefore in no difference in CAPEX. In other words, the difference in CAPEX is zero, a value that still is relevant for determining the MAC.

OPEX (fixed)
The fixed OPEX is derived from literature if any information is available. If not, the assumption is made that the OPEX (fixed) is 5% of CAPEX. This assumption follows from a range of fixed OPEX stated in a report of the European Union for sustainable energy investments (EU, 2016). Similar to calculating the difference in CAPEX, it depends on the characteristics of the decarbonisation options whether the fixed OPEX of the reference technology is subtracted.

Specific energy consumption
The specific energy consumption [GJ/t] depends on the characteristics of the decarbonisation option and reference technology and determines, in combination with the fuel costs [€/GJ], the difference in OPEX (variable). The specific energy consumption is derived from the energy flows from the system of interest (see section 3.2), that show how much energy should be delivered by the decarbonisation option (or reference technology).

OPEX (variable)

The variable OPEX is calculated by multiplying the specific energy consumption with the annual production in tonnes and the related fuel costs. When variable OPEX of the decarbonisation option and the reference technology is calculated, the variable OPEX of the reference technology is subtracted from the variable OPEX of the decarbonisation option.

CO_2 emissions

The CO_2 emissions that result from operating the decarbonisation option[16] are subtracted from the emissions of the reference technology for the specific process step(s). Please note that this is the other way around compared to the difference in CAPEX and OPEX. The resulting difference in CO_2 emissions determines the savings in cost because the CO_2 tax can be deducted from the cost balance. As earlier explained in the theoretical framework, this CO_2 tax is an intangible externality.

Lifetime

The lifetime of the decarbonisation option is also assumed to be its depreciation period and is not affected by the reference technology. This assumption is based on several studies which state that the life expectancy (i.e. the lifetime in this thesis) stands for the physical life of each part and the usage years of the technology. When the usage years exceed the life expectancy, the residual value becomes zero (Hasegawa, Kinoshita, Yamada, Inoue, & Bracke, 2018). In other words, the depreciation period has ended. The lifetime determines, together with the discount rate, the capital recovery factor. This is further elaborated in subsection 3.3.3.

Fuel prices

The fuel costs play an important role in the ceramic industry, as the share of energy costs in the cost price of the final product is approximately 30% (KNB, 2020). This means the industry is very energy intensive and different energy prices are important indicators for investment decisions of ceramic plants. The prices of energy for the year 2030 are determined from literature are assumed to be constant in the scenario analysis. However, the calculation model is built in such way that these prices can easily be altered to apply sensitivity analysis. The following energy prices are included in this thesis, listed below with a brief explanation and literature sources included:

- **Electricity (14.72 €/GJ)**: The price of electricity is set to 14.72 €/GJ (45.79 €/MWh), taken from the Dutch 'Klimaat and Energieverkenning' (KEV) 2019 (Climate and Energy Outlook). This value is the average price of the base load from 2020 to 2034. (PBL, et al., 2019). Comparing this price with other scenario studies shows that it is slightly lower than the 50 €/MWh applied in those studies (Brynolf, Taljegard, Grahn, & Hansson, 2018).

- **Natural gas (7.50 €/GJ)**: The natural gas price (LHV[17]) is also taken from the KEV and set to be 7.50 €/GJ (27€/MWh). In contrast with the electricity price, this natural gas price is higher than the natural gas price used in the scenario study by Ball, Wietschel, & Rentz (2007), who state a price range of natural gas from 16 - 19 €/MWh in their scenarios for 2030.

- **Hydrogen (30.28 €/GJ)**: Only green hydrogen[18] is used in this thesis, which price is estimated to be 30.28 €/GJ (109 €/MWh) based on the estimation by (Elzenga & Lensink, 2019) and a 30% decrease of costs in 2030 (IEA, 2019). This value is

[16] For decarbonisation options this value could be zero.
[17] Low Heated Value, also known as Low Calorific Value. Energy content is 0.03165 GJ/m^3 (RVO, 2020).
[18] It is assumed that green hydrogen has the same energy content as grey hydrogen, 0.01080 GJ/m^3 (RVO, 2020).

considered optimistic when being compared with a study on a hydrogen supply chain network in Germany, which concludes on a green hydrogen price of 290 €/MWh in 2030 and 278 €/MWh in 2050 (Bique & Zondervan, 2018).

CO_2 tax

In this thesis it is assumed that a CO_2 tax is present, without any free allocated space. This CO_2 tax is regulated by the European Commission and its price is set to a constant value of 47 €/tCO_2, derived from the KEV 2019 (PBL, et al., 2019). If a Dutch CO_2 tax also is present in 2030, it is assumed that this Dutch CO_2 tax is below the European CO_2 tax, i.e. below 47 €/tCO_2. The CO_2 tax is only included in the MAC calculations from a private perspective.

3.3.3 Calculation of MAC

To calculate the MACs, the following equations in this subsection are adapted from Blok & Nieuwlaar (2017). Several assumptions are included in the equations, for example the annual costs that are constant throughout the lifetime of the decarbonisation options. This might be a too simplified representation of reality, but will be solved to a certain extent by applying a sensitivity analysis on the fuel prices and discount rates. This application of a sensitivity analysis answers part of the criticism that is discussed in the research approach (see section 1.4). The first equation calculates the MAC:

$$C_{spec,CO_2} = \frac{\alpha \cdot I + C - B}{\Delta M_{CO_2}} \qquad (3.4)$$

Where C_{spec,CO_2} [€/tCO_2] is the MAC, α is the capital recovery factor, I [€] the investment cost, C [€/yr] the annual costs and B [€/yr] the annual benefits. ΔM_{CO_2} [tCO_2/yr] is the annual CO_2 abatement.

The capital recovery factor is a function of the discount rate and the lifetime of the decarbonisation option, given by the equation:

$$\alpha = \frac{r}{1-(1+r)^{-n}} \qquad (3.5)$$

Where α is the capital recovery factor, r is the discount rate and n [yr] is the lifetime of the decarbonisation option. The equation shows that the capital recovery factor will always be larger than (or equal to, in case of infinite lifetime) the discount rate. For a longer lifetime the capital recovery factor will be closer to the discount rate.

3.4 BCA method

The BCA will be approached by means of comparing different decarbonisation options to determine what option can best be implemented in the production process of the ceramic plant. Such a comparison enables justification for undertaking a project or not, based on the estimated costs against anticipated benefits (Axelos, 2017). The comparison of these decarbonisation options is determined by several evaluation parameters. The BCA in this thesis will apply the parameters NPV, IRR and PBP, which are discussed in the subsections below. An interesting feature of using the combination of these parameters is that each has a different parameter unit, i.e. [€] for NPV, [%] for IRR and [years] for PBP.

The other parameters stated in the theoretical framework will not be used, because those parameters are not directly applicable to the information that will be retrieved from the system analysis and MAC analysis. For example, the profit margin requires information about the both costs and sales to determine the profit. However, sales numbers will not be known in this thesis because the focus is on costs and the cost-effectiveness of decarbonisation options. And the levelized cost of energy is neither applicable to the BCA in this thesis because energy is an input parameter and no output value of the system analysis.

The theoretical framework discusses the difference between social and private discount rates. From this discussion it follows that a private discount rate should be included in the BCA of the decarbonisation options. Figure 6 shows that this private perspective (which is related to the private discount rate) is used to calculate the NPV, PBP and IRR. Those three project evaluation techniques, as being referred to by Remer, Stokdyk, & van Driel (1993), have been applied for the last decades in the decision-making process by industrial companies. Literature shows that the three evaluation techniques are applied in techno-economic analysis of renewable technologies, such as biomass gasification (Cardoso, Silva, & Eusébio, 2019), and another paper relates to these techniques as main financial indicators for the analysis of wave energy farms (Guanche, de Andrés, Simal, Vidal, & Losada, 2014). Therefore, these three parameters are also used in this thesis, assembled in the BCA method.

Since the private perspective is applied for the BCA, the externality of a CO_2 tax is included. As discussed in the theoretical framework (see Figure 4), this solves on of the limitations of the neoclassical economics approach. Moreover, it solves to some extent the limitation discussed by Kuckshinrichs & Koj (2018), that environmental costs are not part of the decision-making process of the market parties. However, the CO_2 tax still has no direct effect on the private discount rate, which is used for analysing the NPV and IRR.

3.4.1 Net present value

The value of the NPV gives a first indication whether one option is a better investment than the other. The net present value is calculated by the following equation:

$$NPV = -I + \frac{B-C}{\alpha} \qquad (3.6)$$

Where NPV [€] is the net present value of the project at the beginning of 2030. The capital recovery factor is the same as the recovery rate stated in equation 2.5, and is therefore dependent on the discount rate and lifetime of the option. Even if the decarbonisation option has negative annual cost, a business case is possible when the difference in costs between the reference technology and the decarbonisation option can be positive[19]. Furthermore, the CO_2 cost is included in the annual costs of the reference technology as carbon tax by the European Commission. Depending on the degree of abatement of the decarbonisation option, this CO_2 tax will have a positive effect on the NPV.

3.4.2 Internal rate of return

The second parameter is the internal rate of return (IRR). This rate gives a better indication for the attractiveness of an investment or when two decarbonisation options, for example, need to be compared. And an advantage of this method compared to the NPV is that the IRR is less influenced by the size of the investment, which enables better comparison between decarbonisation options. The internal rate of return is the discount rate at which the net present value would be zero. When the NPV is positive, the IRR is always higher than the discount rate. Typically, a minimum value for the IRR of 10% is desired, which is usually

[19] For example, if the reference technology has annual benefits minus annual costs that equals -100,000 € and the decarbonisation option has annual benefits minus annual costs that equals -60,000 €, the difference is positive: -100,000-(-60,000) = 40,000 €.

higher than interest rates applied by banks (Blok & Nieuwlaar, 2017). However, it is unsure whether this rate of 10% is also applicable to the ceramic industry. No specific rates for the ceramic industry are described in literature. Furthermore, an academic paper that analyses the charcoal industry, applies a minimum value of 15% (Silva, Cardoso, Varanda, Christoforo, & Malinovski, 2014). However, it is unknown to what extent charcoal industry can be compared to the ceramic industry.

3.4.3 Pay-back-period

Since the NPV is an absolute figure, it might give an insufficient indication of a business case. Therefore, a third parameter is included in this thesis. This parameter is the pay-back-period (PBP), which shows in how many years the investment costs are returned. This thesis follows the 'Wet Milieubeheer' (law of environmental management) which states that a decarbonisation technology should have a PBP of 5 years or less (RVO, 2019).

The PBP is given by the following equation:

$$PBP = \frac{I}{B-C} \tag{3.7}$$

Where I [€] is the initial investment, and $B - C$ [€/yr] is the annual difference in costs between the reference technology and the decarbonisation option. The PBP is considered a rule of thumb since it is straightforward and relatively easy to determine, but it ignores any changes in annual costs or benefits. Moreover, it does not include the discount rate.

3.5 Concluding on the methodology

This chapter has discussed how the theory of the theoretical framework (see chapter 2) will be applied to analysing the decarbonisation of the ceramic industry in the Netherlands, with specific methods and input parameters. An important contribution of this chapter is the description of sources of input parameters and clarification of assumptions when sources are unavailable. No sub research question is answered by this chapter.

The chapter begins by explaining the starting point of the research and how the normative scenario type and techno-economic perspective can be translated into the different method and tools. The first methodological step is to provide an overview of the system, which is conducted by thorough desk research, consultation with experts and applying an input-output analysis with mass and energy flow equations. The results of this system analysis are stated in the next chapter. The third methodological step is computation of the MACs and construction of MAC curves. This analysis is conducted from both a social and private perspective. The private perspective is also used by the last methodological step, which is the BCA that used the NPV, IRR and PBP as evaluation parameters.

4 Overview of the ceramic industry

This chapter provides an overview of the ceramic manufacturing processes and relevant decarbonisation options. This enables answering *SQ2*: *"What is the current state of the ceramic sector in terms of processes and CO_2 emissions?"* Furthermore, it provides a first step in answering *SQ3* and *SQ4* by providing an overview of the decarbonisation options and their techno-economic parameters.

The chapter is structured as follows. First, section 4.1 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 scope of this thesis. Second, section 4.2 states the results from empirical research and input-output analysis, which is a description of the calculation steps and diagram of the calculated mass, energy and CO_2 emissions flows for each of the different product types. Third, section 4.3 describes the decarbonisation options that are applicable to the critical processes of the ceramic industry. To enable comparison with the current situation, a description of the reference technology for each of the critical process steps is given too. If possible, techno-economic parameters are discussed for the decarbonisation options. Such parameters are, for example, the specific energy requirements, specific CO_2 emissions and required supply of feedstock. Finally, section 4.4 concludes on the system analysis and answers *SQ2*.

Because the focus of this thesis is on the ceramic industry in the Netherlands, only plants located in the Netherlands are analysed and the desk research focuses on the literature that describes the ceramic production processes, decarbonisation options and other parameters (e.g. supply of feedstock) that concentrates on the Dutch or a similar environment.

4.1 Production of ceramics

The production of ceramics is divided into three 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 and wall tiles;
- Refractory products.

The manufacturing of bricks can be subdivided in three categories: facing bricks, paving bricks and inner wall bricks. The total production of all ceramic plants in the Netherlands approximates 2.7 million tonnes. Figure 8 shows that mostly bricks are produced (85% out of total production) and that facing bricks (placed in the outer wall of a building) cover more than half of the ceramic production in the Netherlands. See Appendix A and Appendix B for a detailed description of all ceramic companies and plants, respectively, and their production volumes and CO_2 emissions.

The two subsections 4.1.1 and 4.1.2 give a general description of the ceramic production process in the Netherlands and corresponding emissions, respectively.

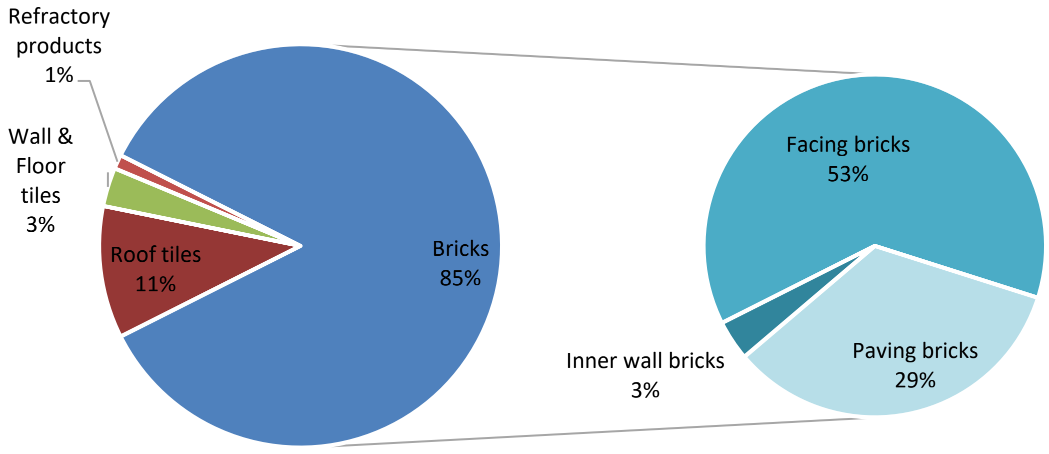


Figure 8. Production share of tonnes ceramic products manufactured.

4.1.1 General description of production process

The manufacturing process of ceramic products is subdivided in six general process steps (see Figure 9): mining and storage, preparation, shaping, drying, firing and subsequent treatment. Only processes taking place within the plants are part of the scope of this research. The first block, 'mining and storage', will therefore be shortly described in this section but is not included in this thesis in terms of energy consumption. The product specific production processes are elaborated in Appendix C.

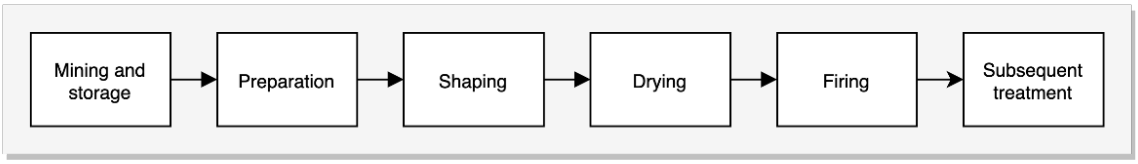


Figure 9. General overview production processes ceramic plants.

Mining and storage

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', consists 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).

Preparation

The first manufacturing process within the plant is preparation of the clay raw material. This includes increasing the water content for higher plasticity, creating a smaller particle size (e.g. by spray drying) and addition of supplementary materials. Furthermore, different types of clay raw material may be mixed. The exact preparation differs per product and is explained more in detail in Appendix C.

Shaping
Pre-dried material (also named ‘green ware’ (EC, 2007)) 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.

Drying
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, plans have a nearly closed water system.

Firing
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 recrystallization 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 and usually is 1 to 1.5 $vol_{\%}$ of the total mixture (the other part is natural gas) (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.

Subsequent treatment
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.

Figure 10. Storage yard (in Dutch ‘kleidepôt’) where extracted clay is stored, often closely located to the ceramic plant. Source: (KNB, 2020).

4.1.2 Emissions

CO_2 is emitted during ceramic production from burning fuels like natural gas (fuel emissions), or from chemical reactions of carbonates (process emissions). These chemical reactions are also referred to as calcination (EC, 2007). 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 gases are: spray drying (only wall & floor tiles), drying and firing. These three processes are assumed to all use natural gas as energy source. This assumption is based on communication with experts from the KNB. 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 by 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 and does not add up to the CO_2eq emissions (KNB, 2020). This is also the reason that CO_2eq is considered the same as CO_2 in this thesis. CO_2eq will only be mentioned when it is directly taken from literature (e.g. in Table 1).

Figure 11 states the calculated average CO_2 emissions per tonne end product. At the end of each of the sections below, energy & material flow diagrams (resulting from the input-output analysis) are given that include the CO_2 emissions numbers for each product category more into detail.

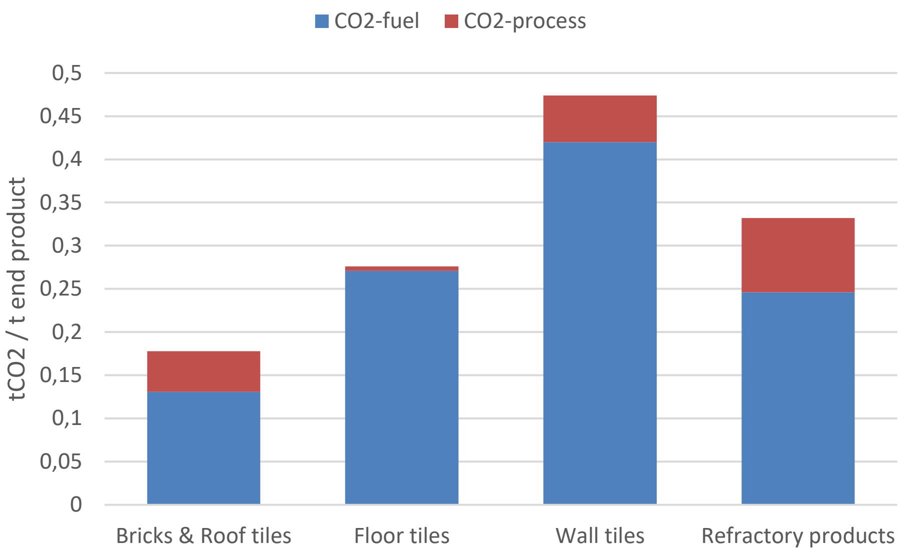


Figure 11. CO_2 emissions per tonne of end product per product type. Blue part of the bar are emissions from burning fuels and red part are the process emissions. Source: own calculations.

4.2 Mass, energy and CO_2 emissions flows

The subsections below describes the mass, energy and CO_2 emission flows for the ceramic products, distinguished in three categories: first bricks and roof tiles, second floor and wall tiles, and third refractory products. The specific descriptions of the production processes of each of these products are stated in Appendix C.

Each subsection first describes the different calculations and assumptions that are made, including sources of literature. This is followed by explaining the construction of the process flow diagram, based on the input-output analysis (see section 3.3).

4.2.1 Bricks and roof tiles

Figure 12 provides the material, energy and CO_2 emissions flow diagrams for brick manufacturers and roof tile manufacturers. The total energy consumption is 2.55 GJ per tonne end product. This consists of 0.24 GJ_e (electricity) and 1.31 GJ_{th} (natural gas). These values are determined in the following steps:

1. The CO_2 process emissions percentage of the total CO_2 emissions are calculated based on an estimated 6200 TJ natural gas consumption in 2015 (RVO, 2016), which is multiplied by 56.6 $kgCO_2$/GJ natural gas (RVO, 2017), and divided by 477,079 tCO_2 registered EU ETS emissions in 2015 (Dutch emissions authority, 2020). This results in a process emissions part of the total CO2 emissions of 26%;

2. The sum of the EU ETS registered emissions in 2016 is taken for the companies producing bricks 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 WF bricks. 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 divided by 2,260,017 tonnes, which results in 0.131 tCO_2/t brick;

3. It is assumed the combustion fuel consists solely of natural gas (see subsection 4.1.2). The specific natural gas consumption of bricks is therefore 0.131 tCO_2/t brick multiplied by 0.0566 $kgCO_2$/GJ, which results in 2.3 GJ/t bricks;

   a. The specific natural gas consumption of the firing section is assumed to be 0.087 m^3/brick (Steenfabriek de Rijswaard B.V., 2020). Assuming the bricks are expressed in 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[20] (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.

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_2 emissions (0.177 tCO_2/t brick) and the registered EU ETS CO_2 emission data for 2016 (Dutch emissions authority, 2020). A range was applied assuming the accuracy of the calculation to be +10% and -10%. 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 (see Table 21 in Appendix B).

Figure 12 shows that the five process blocks (see Figure 9) are simplified into two process blocks. The original process blocks are simplified into two blocks because no specific

[20] This has also been confirmed by the KNB 'working group environment and energy'.

information could be derived from certain process steps. In addition, process steps that only require electricity as energy input are not relevant to this thesis. Resulting from this, the preparation, shaping and drying process step are combined in the first block. It can be seen that the CO_2 fuel emissions output flow of this block is 0.046 tCO_2/t, which results only from the drying process. As explained in the calculation steps above, additional heating (next to using the residual heat from the firing process) is provided by burning natural gas

The second block in Figure 12 is a combination of the firing and subsequent treatment. This block shows an output of fuel emissions (0.085 tCO_2/t) and process emissions (0.047 tCO_2/t). The fuel emissions are the result of firing the bricks (or roof tiles) by natural gas, and the process emissions are the result of chemical process calcination of the ceramic material. Subsequent treatment requires only electricity as energy input. The electricity consumption is assumed to be equally distributed to the 'Preparation, shaping, and drying' and 'Firing and subsequent treatment'.

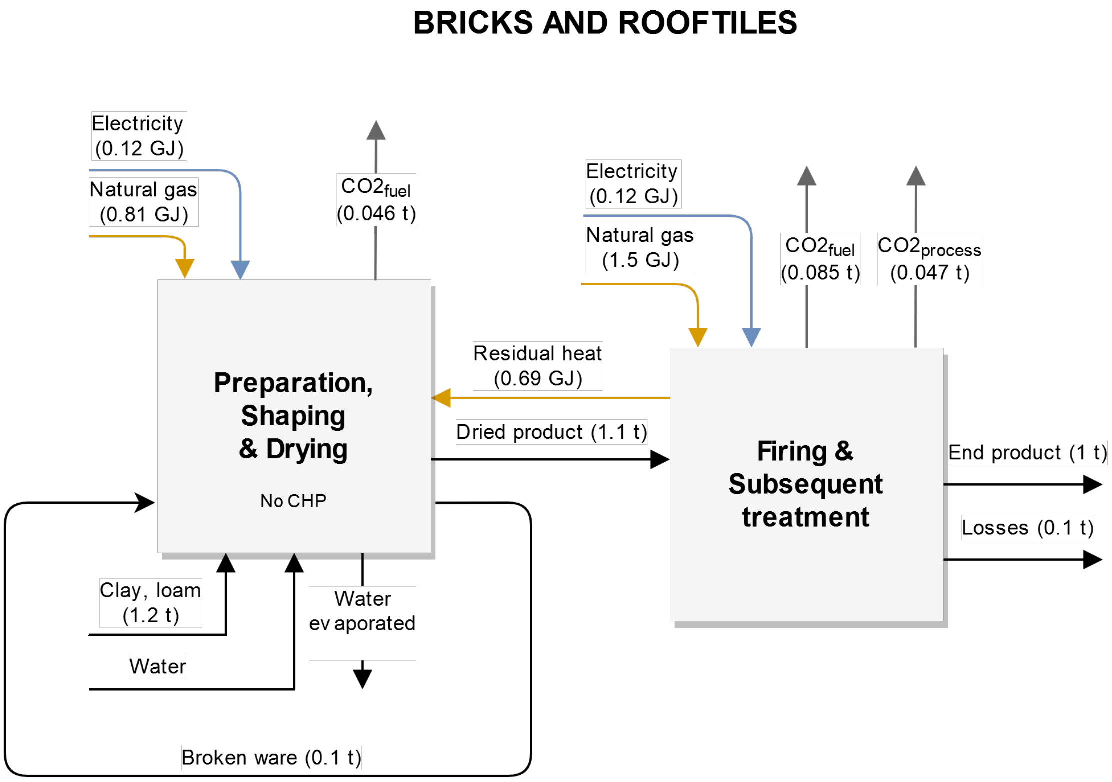


Figure 12. Flow diagram of the manufacturing process of bricks and roof tiles, including mass, energy and CO_2 emissions flows. Applicable to plants without gas-fired CHP.

4.2.2 Wall and floor tiles

Figure 13 and Figure 14 show the material, energy and CO_2 emissions flow diagram of floor and wall tiles. The total specific energy consumption for natural gas and electricity were taken from (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[21] for these processes in floor and wall tiles production from the BREF (EC, 2007).

The production volumes for 2016 of the two tiles producing plants was calculated using the data on material consumption and waste production of a sustainability report of Mosa (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 (Nea, 2020). And the calculated CO_2 emissions from natural gas combustion (based on the total produced tiles multiplied with the specific natural gas consumption).

The total energy consumption is 7.63 GJ/t and 10.22 GJ/t for floor tiles and wall tiles, respectively. The difference between these total energy consumptions can for a big part be related to firing process, during which wall tiles have an extra biscuit firing step. Compared with the flow diagram of bricks and roof tiles (see Figure 12), the figures show three process blocks instead of two to describe the process flows. The additional block is created to distinguish the spray draying (during the preparation processes) from the actual drying process. The amount of residual heat extracted from the firing section used for drying could not be determined.

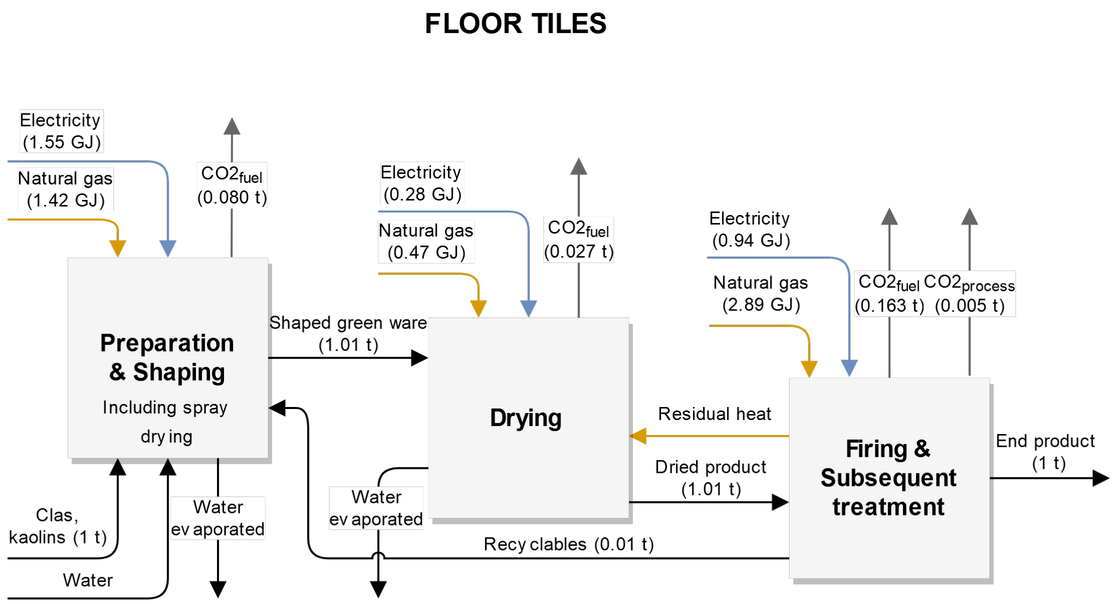


Figure 13. Flow diagram of the manufacturing process of floor tiles, including mass, energy and CO_2 emissions flows.

[21] The average was taken for ranges in the BREF document (EC, 2007).

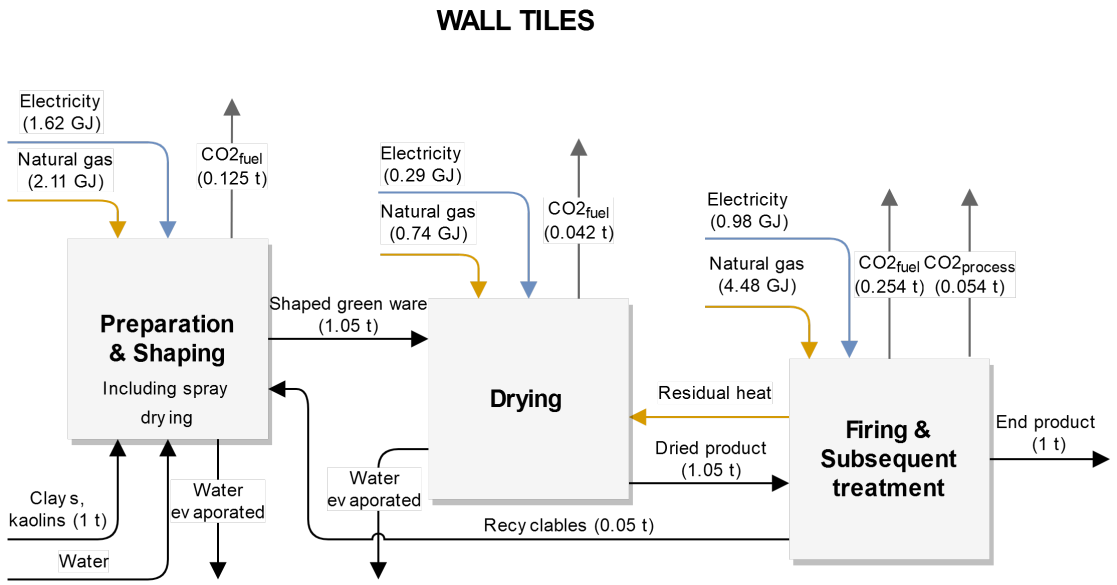


Figure 14. Flow diagram of the manufacturing process of wall tiles, including mass, energy and CO_2 emissions flows.

4.2.3 Refractory products

Figure 15 shows the material, energy and CO_2 emissions flow diagram of refractory products. For refractory bricks, specific CO_2 emissions of 0.3225 tCO2/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.

The natural gas consumption was calculated by subtracting the process emissions from the total specific CO2 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 and subsequent treatment'.

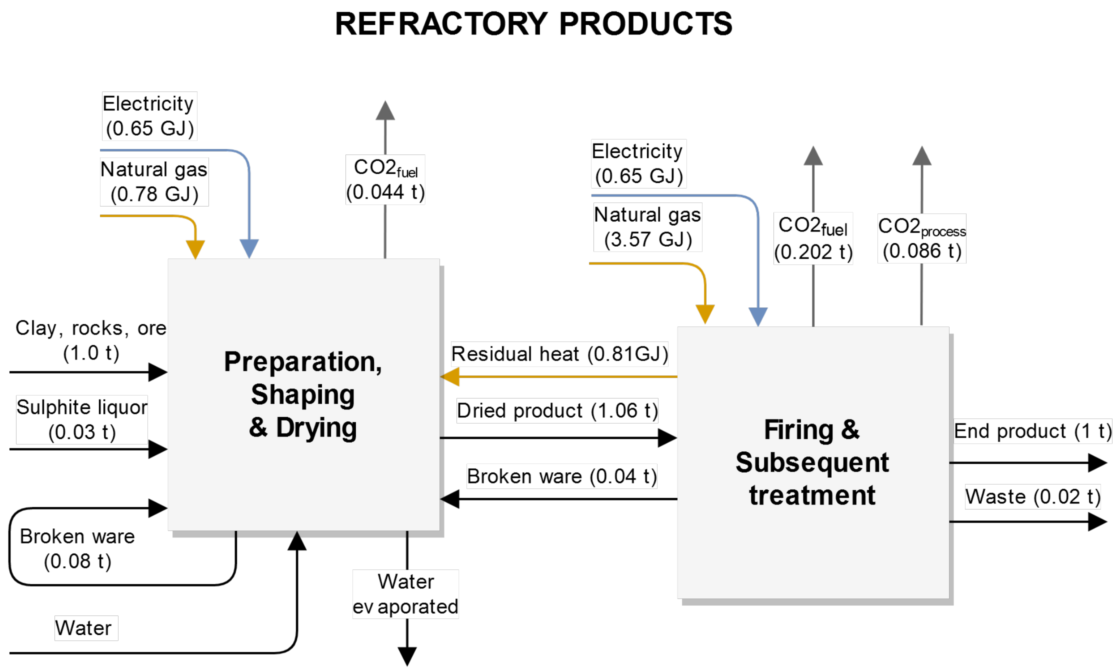


Figure 15. Mass, energy and CO_2 emissions flow diagram of refractory products. Material amounts are taken from the BREF example of production of periclase chromite bricks (EC, 2007, p. 112).

4.3 Options for decarbonisation

The previous sections have described the different ceramic production processes. The processes are distinguished in four types based on the type of product. For each type of product different mass, energy and CO_2 emissions flow diagrams are provided at the end of the corresponding subsection. These figures show that drying and firing are the two critical process steps, i.e. the process steps that have CO_2 emissions as output flow.

Since bricks and roof tiles together have a production share of more than 95% in the Netherlands (see Figure 8), their drying and firing process steps (see Figure 12) are used to determine options for decarbonisation and further calculations with those decarbonisation options. It is therefore assumed that the decarbonisation options discussed in this section are also applicable to the production processes of roof tiles, wall tiles and refractory products.

Reference technology

Before an overview of the decarbonisation options is given, the reference technology is described. This reference technology is partly or fully replaced by the decarbonisation option (see subsection 3.3.2) and is required to perform the calculations for the MAC and business case analyses. This reference unit is based on a gas fired bricks and roof tiles plant, since these are the most common manufactured products in the Netherlands. Table 3 states the different parameters of this reference unit that are used in the calculation method. The lifetime and CAPEX of the reference technology is based on communications with the ceramic industry, which gave a cost number for a plant with an annual production that is higher than 80 kt. After scaling down, the CAPEX became 12 M€ for a ceramic plant with a production of

80 kt. The OPEX (fixed) is assumed to be 5% of CAPEX, adapted from a range of fixed OPEX from the Sustainable Energy Handbook of the European Union (EU, 2016). This results in an annual OPEX (fixed) of 0.6 M€. The CAPEX and OPEX of the reference technology are only applicable to the firing process. The specific energy consumption (SEC) in the drying process is not 1.5 GJ/t but 0.8 GJ/t, because it is assumed that 0.7 GJ/t is supplied as residual heat from the firing process. Finally, the table states the annual CO_2 emissions for each of the critical processes (i.e. drying and firing) and the related annual process emissions, which is 26% of the total annual CO_2 emission.

Table 3 Parameters for the reference gas fired drying and/or firing option.

Parameter	Unit	Value
Lifetime	yr	30
Production	kt/yr	80
CAPEX	M€	12
OPEX (fixed)	M€	0.6
SEC firing	GJ/t	1.5
Specific CO_2 emissions firing	ktCO_2/yr	6.77
SEC drying	GJ/t	0.8
Specific CO_2 emissions drying	ktCO_2/yr	3.61

Overview of decarbonisation options

The decarbonisation technologies are identified through desk research of publicly available sources. The two most important sources of information were the British decarbonisation roadmap to 2050 (PB & DNVGL, 2015) and research conducted by the TCKI. Unfortunately, it has not been possible to assess the decarbonisation options to a specific plant or more plants from one of the ceramic companies by means of a case study. As a result, the decarbonisation options could not been validated or discussed in detail with the ceramic industry. Nevertheless, the overview of decarbonisation options and their applicability is generally discussed with different ceramic companies (e.g. Braas Monier, Vandersanden, and Wienerberger) during a meeting that was initiated by the KNB.

Different categories of decarbonisation options are identified by the MIDDEN project team to ensure a clear overview of the applicability and type of decarbonisation option (see Figure 16). The decarbonisation options that are identified in this thesis for the ceramic industry do not cover all categories in Figure 16. For example, recycling of material and water is already applied by most ceramic plants (see for more information Appendix A).

The categories that are covered by the decarbonisation options are:

- Fuel substitutions;
- Process design (both efficiency increase and substitution);
- Use of residual energy;
- CO_2 capture and storage (CCS) or re-use.

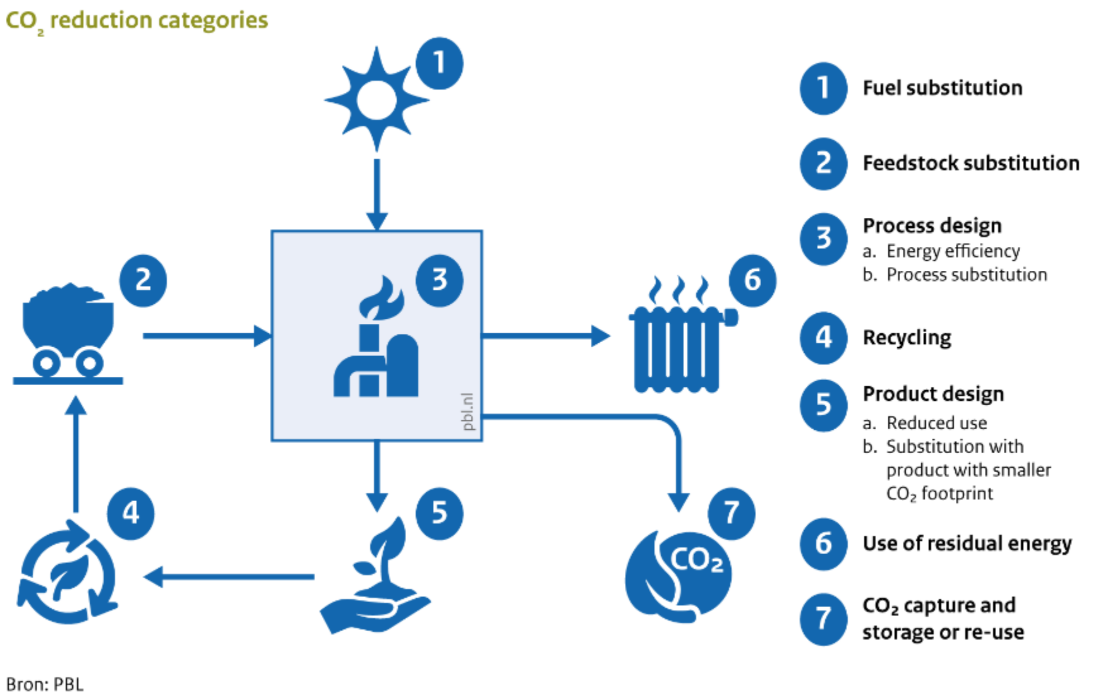


Figure 16. Different CO_2 abatement categories identified by the MIDDEN project of PBL and ECN (part of TNO).

Considering the category feedstock substitution, several literature has described the potential of a different raw material input for a more sustainable ceramic production process. For example, the use of paper mill sludge (Goel & Kalamdhad, 2017) or waste glass sludge (Kazmi, Munir, Wu, Hanif, & Patnaikuni, 2018). Another paper describes the use of ash from biomass (Eliche-Quesada & al., 2017). These three papers have in common that they aim for a more sustainable production process by the use of material input that is the waste output of other processes. However, in the Netherlands this is not necessarily an important topic for decarbonising the ceramic industry, since most plants extract their clay raw material from the embanked floodplains along the rivers they are located next to. Therefore, transport costs are already minimised. Besides that, such floodplains renew themselves each year and ceramic plants create nature reserves by extracting clay from the floodplains (KNB, 2020).

Table 4 provides an overview of the different decarbonisation options that are applicable to the ceramic industry in the Netherlands. The techno-economic parameters in Table 4 are determined for plants with a production capacity that is the average of production capacity of all bricks and roof tile plants. This represents 96%[22] of the total ceramic industry in the Netherlands.

The stage of development and availability of options is distinguished in four stages: concept, lab scale, pilot scale and commercially available. Furthermore, please note that the amount of process emissions (26% of total CO_2 emissions) is included in the calculations of maximum CO_2 abatement. The total CO_2 emissions that can theoretically be abated is 14,000 tonnes, which is the annual CO_2 emissions of one regular bricks and roof tiles plant (see Table 3). The following section describe all decarbonisation options and their techno-economic parameters in detail.

[22] In terms of production in tonnes (see Figure 8).

Table 4 Overview of abatement options, including techno-economic parameters.

Name option	Category	Process	Lifetime (years)	CAPEX (M€)	Total OPEX (M€)	Max. CO_2 abate-ment	Availability
Green gas (gasification)	Fuel substitution	Drying & Firing	25	18.4	1.29	74%	Commercially available
Green gas (digestion)	Fuel substitution	Drying & Firing	25	6	0.52	74%	Commercially available
Hydrogen	Fuel substitution	Drying & Firing	30	10	0.78	74%	Lab scale
Electric kiln and drying	Fuel substitution	Drying & Firing	30	22	11	74%	Concept
Microwave kiln and drying	Fuel substitution	Drying & Firing	Unknown	Unknown	Unknown	74%	Concept
Heat recovery	Residual energy	Drying	Unknown	Unknown	Unknown	26%	Pilot scale
Industrial heat pumps	Residual energy	Drying	12	2.5	0.06	26%	Commercially available
Hybrid drying	Residual energy	Drying	Unknown	Unknown	Unknown	Varies	Pilot scale
Ultra-deep geothermal	Process design	Drying	25	5.6	0.24	26%	Commercially available
Extended tunnel kiln	Process design	Firing	30	Unknown	Unknown	Varies	Commercially available
CCS or utilisation	CCS or re-use	Drying & Firing	25	20	1.37	90%	Commercially available

4.3.1 Green gas

Green gas (also named 'biomethane') can directly replace natural gas and is therefore considered a fuel substitution. It can fully substitute the natural gas, or be used as co-firing in the ceramic industry (Leicher, Giese, Al-Halbouni, & Görner, 2016).

This means that no alterations are required in the production process and additional costs are only resulting from the production and transport of green gas. If green gas is centrally produced on a large scale, 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. This is because the green gas from the grid will replace (fully or partly mixed) the natural gas supply from the grid. Furthermore, the production of green gas could be combined with a negative emission technology which captures the CO_2 that is emitted during the production of green gas. This combination of technologies is referred to as bioenergy with carbon capture and storage (BECCS) (Bui, et al., 2018).

Below, two technologies are discussed that produce green gas on-site. The first technology makes use of anaerobic digestion, and the second technology of gasification. Anaerobic digestion is preferred for wetter biomass material and gasification is preferred for dryer biomass material (Lensink, 2020). Both technologies are located at the plant's site and are therefore scaled to produce the required amount of gas for the production process of a plant with a production capacity of 80kt (see Table 3). This required amount of gas is approximately six million m^3 per year, which is calculated by multiplying 80 kt production with the 2.3 GJ/t SEC, and dividing the result by the lower calorific value of gas: 31.65 MJ/m^3 (RVO, 2020).

On-site anaerobic digestion (biogas)

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 formed biogas can then be converted into green gas by removal of non-methane elements (mostly carbon dioxide) by a membrane filtering technology, which is scalable (Lensink, 2020).

The supply of feedstock for anaerobic digestion is important to consider, including the nearby availability, corresponding costs and present infrastructure. A study by Kampman, et al., (2016) states that a large potential for solid and liquid manure (e.g. from cattle) as feedstock for biogas production is available after 2020. In addition, using this type of feedstock has less impact on the climate than, for example, making use of crop digestion (Kampman, et al., 2016). This is because methane emissions are avoided when choosing for the manure as feedstock. Furthermore, Kampman, et al. (2016) show by empirical research that small biogas plants prefer to use manure, while bigger biogas plants use organic waste. Therefore, biogas production with manure as feedstock is considered the best applicable option in the case of producing on-site green gas for ceramic plants. This coincides well with the fact that renewable heat production from manure is eligible under the SDE+ scheme for heat generation using gas (ECN & DNV GL, 2016).

However, the question still arises whether sufficient feedstock is available, which preferably should be supplied from nearby cattle farms to prevent high transportation costs. According to the SDE++ advice, 25 m^3 biogas is produced per tonne manure, thus the required input of manure would be approximately 240 kt per year. To determine whether it is feasible to supply this amount of manure, the average yearly production of manure by one dairy cow is on average 26 m^3 per year (RVO, 2019). Assuming that the weight of one m^3 manure is a tonne, and that each part of this manure can be used for the digestion, this means that on average a minimum of 9,231 cows is needed. The digestion of dairy manure for the production of biogas has also been researched by Ledda, et al. (2016), who concluded that a dairy farm with 1200 cattle produced in total 16 kt manure per year that could be used for the production of biogas. The production of manure per dairy cow is almost two times lower than the number stated by the RVO, and would mean that at least 18,000 cows are needed to produce the required manure. Taking both numbers into account, a range of 9,000 to 18,000 dairy cows is required to enable sufficient production of biogas. In the Netherlands, cattle farms own on average 97 dairy cows and have 60 ha of space (Peet, et al., 2018). This means that 100 to 200 cattle farms (with 600 – 1200 ha of total space) are required to supply an average sized ceramic plant.

Despite the fact that 100 to 200 farms is a big number, it is only 0.5 to 1% of the total amount of farms with dairy cattle in the Netherlands[23]. Furthermore, in the above analysis of the supply of manure, only dairy cattle is included and no other cattle, such as pigs. Looking

[23] The total amount of dairy farms in the Netherlands is 17,910 (Peet, et al., 2018).

at the total production of manure by all cattle in the Netherlands, the numbers show that cows make up more than 80% of all cattle (CBS, 2020).

Techno-economic parameters
Table 5 shows information about the cost for an installation with a production capacity of 750 m^3 green gas per hour. Considering constant operation (i.e. 8000 hours per year in this case), the provided energy by the upgraded biogas would be 184 TJ. This amount of energy from green gas is sufficient for a regular ceramic plant with an annual production 80 kt[24].

Table 5 Techno-economic parameters for a large-scale production unit of green gas using digestion. Source: Adapted from (Lensink, 2020).

Parameter	Unit	Value
Power (output) per year	TJ	184[1]
Investment costs (CAPEX)	M€	6.00
O&M costs (fixed OPEX)	M€/yr	0.52
Feedstock costs	€/GJ	8.18

[1] 80,000 t production per year * 2.3 GJ/t = 184,000 GJ per year.

Furthermore, it is described in literature that waste from biogas installations, called fermentation residues, could be use as input raw material for the manufacturing process or brick. The results from a pilot study show that mixing this waste (5%) with the conventional raw material results in an improvement of porosity and bulk density, but has negative effects on the water absorption and compressive strength (Šál & Nováková, 2019). In addition, it lowers the costs as overall waste is decreased. Nevertheless, the effect of mixing the waste with raw material should further be researched and an important criteria is of course that there is sufficient waste available to create a significant effect on the cost reduction.

On-site gasification of biomass (syngas)
Besides anaerobic digestion, on-site gasification could 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 can directly be used as fuel or feedstock instead of being converted in 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.

Techno-economic parameters
Table 6 shows the associated techno-economic parameters and costs for production of green gas by gasification of biomass (Lensink, 2020). Because the parameters from Lensink (2020) are only applicable to large consumers of green gas, an adjusted column is added to Table 6. This column states the associated parameters in case of a scaled down installation, suitable for a regular ceramic plant. Similar to the on-site digestion, it is an important criteria that the feedstock (biomass) is available. Table 6 shows that on a yearly basis, more than 20 kt[25]

[24] Table 20 in Appendix B shows all estimated production numbers of the ceramic plants in the Netherlands. The average production number is approximately 80,000 tonnes.
[25] 184 TJ / 9 GJ/t = 20,444 t.

of biomass is required. This amount of feedstock is significantly less than needed for anaerobic digestion, which requires 240 kt per year. Nevertheless, the feedstock should be available (preferably nearby) to keep the transportation costs (not included in Table 6) as low as possible.

Table 6 Techno-economic parameters for a production unit of green gas using gasification of biomass. Adapted from (Lensink, 2020, p. 77) and adjusted to fit a regular ceramic plant.

Parameter	Unit	Value	Adjusted value
Power (output) per year	TJ	567[1]	184
Investment costs (CAPEX)	M€	56.70	18.4
O&M costs (fixed OPEX)	M€/yr	3.99	1.29
Feedstock costs	€/GJ	5.00[2]	5.00

[1] Power output is 21 MW * 7500 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.

4.3.2 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 (KNB, 2020). Hydrogen fuel can be categorised based on their production process: grey hydrogen, blue hydrogen, green hydrogen, or a 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[26]. The production of green hydrogen is currently more than three times more expensive as producing grey hydrogen (Elzenga & Lensink, 2019).

Only green hydrogen that is centrally produced and can be extracted from a national grid is considered in this thesis. On-site production of blue or green hydrogen is not considered as a decarbonisation option, because this will not be financially attractive at such a small scale. Furthermore, 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). However, it is unknown whether and when natural gas and its infrastructure would be fully substituted by hydrogen. Bique & Zondervan (2018) argue that transport over rail (when generated in liquid form) could also be a preferred transportation mode, but only if a sufficient railway connection is present.

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;

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

- 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.

Techno-economic parameters

It is currently unknown what burner modifications are needed (further research is proposed by the TCKI) and what the corresponding techno-economic characteristics are. Therefore, it is assumed in this research that the technology of hydrogen burners in 2030 has evolved according to become equal in costs to the current of natural gas burners of the reference technology. Table 7 shows the associated techno-economic characters. Please note that the investment cost of a conventional gas-fired kiln (on which the CAPEX for hydrogen is based) is equal to the reference technology (see Table 3).

Table 7 Techno-economic parameters for a hydrogen fired kiln.

Parameter	Unit	Value
Power (output) per year	TJ	184
Investment costs (CAPEX)	M€	12
O&M costs (fixed OPEX)	M€/yr	0.78

4.3.3 Electric kiln and drying

Electric resistance 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 resistance heating technique is used by pottery bakers. To reach high temperatures (more than 1000 °C), special alloys are used. However, the production capacity of these installations cannot be compared to large scale ceramic plants. Electric resistance heating 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 (PB & 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 it theoretically would be possible for an electric kiln with a capacity of 80,000 t, with an electrical power requirement of up to 10 MW, but this will be a huge challenge (TCKI, 2019). However, this required power could be lower when assuming an efficiency of 100% and the SEC of 2.3 GJ/t. As a result, 6.4 MW of electrical power would be required[27], which is significantly lower than the 10 MW stated by TCKI.

Techno-economic parameters

Despite the unproven application of electric kilns on a large scale, and challenges considering electric capacity of transportation, an approximation is made of techno-economic parameters (see Table 8). These parameters are mainly derived from the Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 for the ceramic sector in the United Kingdom (PB & DNVGL, 2015). This report states that the approximated costs for an electric kiln would be 20 M£, which is assumed to be 22 M€ with a conversion rate of 1.10 €/£. The efficiency is expected to be 100%.

Table 8 Techno-economic parameters for an electric kiln and dryer.

Parameter	Unit	Value
Power (output) per year	TJ	184
Investment costs (CAPEX)	M€	22
Fixed O&M costs (OPEX)	M€/yr	1.1[1]

[1] 5% of CAPEX, adapted from a range of fixed OPEX from (EU, 2016).

In addition to the above costs, the external costs of connection to the electricity grid and increase of grid capacity should be considered. The SDE++ advice states that these costs, based on cost figures of grid operator Tennet in 2019, for the electrolysis for hydrogen production are 49 €/kW/year (Lensink, 2020). Since the peak power of this electrolysis is similar to the 10MW electric kiln power requirement stated by the TCKI, the external costs of capacity increase and connection to the electrical grid would become approximately 0.49 M€/yr according to the required capacity stated by TCKI (2019).

4.3.4 Microwave kiln and drying

Microwave firing and drying, also called microwave assist technology (MAT), 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 (i.e. electromagnetic radiation) 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):

[27] Assuming 8000 operational hours per year, the required power is calculated as:
80,000 t * 2.3 GJ/t / 8000 h / 3600 seconds/h = 0.0064 GW = 6.4 MW.

- 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 can 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 17, 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.

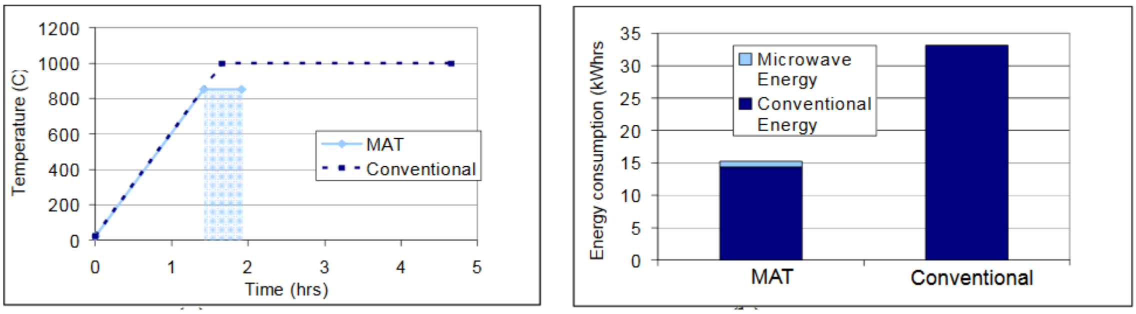


Figure 17. On the left the temperature and duration of the firing process and on the right the total energy consumption. Source: (Shulman, 2007).

This microwave (or infrared) technique could also be combined within an electric kiln, described in 4.3.3, to deliver heat more efficiently to specific high temperature sections of the kiln (PB & 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).

Techno-economic parameters

Since the microwave technology is only a theoretical option with little literature available that elaborates on the technical and economic characteristics, it is not included in the MAC and BCA analyses of this thesis. Moreover, this technology should first be further researched on its applicability (especially the effect of microwaves on the raw material) to the ceramic manufacturing process.

4.3.5 Heat recovery (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 technology has existed since 2009 and is an innovative heat recovery method that solves this deterioration problem by using plastic pipes (PTFE) and recirculating part of the heated air through the flue gas section (TKI, 2019). 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)[28], 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.

Techno-economic parameters

It is unknown what the exact techno-economic characteristics are of heat recovery technologies like Heat Matrix. The technology is still in its pilot phase and no indications have yet been given on the costs for a heat recovery system (from flue gases) that is applicable to a ceramic plant in full operation. Only the efficiency improvement can be determined.

4.3.6 Industrial heat pumps

Industrial closed heat pumps are applicable to the drying process of the ceramic industry. The heat pump allows waste heat from the firing process to be upgraded to a temperature of more than 100 °C, which is sufficient for drying. The heat pump has a closed system which means it circulates water and does not use any waste water, for example. It is assumed in this thesis that adding a heat pump to the process has no effect on the existing flow of residual heat (from the cooling down section) that moves from the firing to the drying process.

Techno-economic parameters

Table 9 gives the techno-economic parameters which are adjusted to an industrial heat pump applicable to a ceramic plant with a production capacity of 80 kt/y. The industrial heat pump has an expected lifetime of 12 years and its variable O&M costs are fully dependent on the electricity price, which is set at 0.053 €/kWh for this example. The efficiency of the heat pump (expressed as the energy output per electricity consumption, or COP) is assumed to be 3.5 (Lensink, 2020). Please note that the variable (electricity) O&M costs, on the last row of Table 9, is not a fixed value but adapted from Lensink (2020). In the scenario analysis, this value will be different due to a different electricity price.

[28] Assuming a yearly operational time of 8000 hours and production of 80,000. The energy required for drying and firing is both 1.5 GJ/t for bricks and roof tiles manufacturers (see Figure 12).

Table 9 Parameters for an industrial closed system industrial heat pump, adjusted to fit a regular ceramic plant. Source: adapted from (Lensink, 2020, p. 115).

Parameter	Unit	Value
Power (output) per year	TJ_{th}/yr	64[1]
Investment costs (CAPEX)	M€	2.5[2]
O&M costs (fixed OPEX)	€/yr	56,000
Variable (electricity) O&M costs	€/GJ_{th}	4.2[3]

[1] Production * energy required for drying process is 80,000 t * 0.8 GJ/t = 64 TJ/yr.
[2] 1,114,000 €/MW * 64,000 GJ / 8000 hours / 3.6 GJ/MWh = 2,475,289 €.
[3] 0.015 €/kWh / 0.0036 GJ/kWh = 4.17 €/GJ. The electricity costs are relatively low due to heat output, which is nearly 4 times higher than the electricity input in MWh. Therefore, the electricity costs expressed in heat output are 0.015 €/kWh instead of 0.053 €/kWh.

It is expected that now problems will occur with the increased electricity consumption by a regular ceramic plant due to the use of industrial heat pumps. Since only 25% of the heat output is electricity input, the input of energy would be 0.2 GJ_e/t[29]. This increases the total electricity consumption per tonne end product to 0.44 GJ_e/t.

4.3.7 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 a lot 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 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. An energy improvement percentage of 25% will be assumed in this thesis.

The hybrid drying technique makes no or little use of the residual heat from the tunnel kiln, therefore a 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 could be by combining this technology with an extended tunnel kiln which is further explained in section 4.3.9.

Techno-economic parameters

Specific techno-economic information about applying hybrid drying is not available in the research related to the pilot project, but costs will come from adjusting the conventional

[29] 64 GJ_{th}/yr / 80,000 = 0.8 GJ_{th}/t. 0.8 GJ_{th}/t * 0.25 GJ_e/GJ_{th} = 0.2 GJ_e/t.

drying chambers (air intake and exhaust, reinforcement and corrosion protection) (TCKI, 2017). Therefore, this decarbonisation option can only be analysed based on its efficiency improvement.

4.3.8 Ultra-deep geothermal

The use of geothermal energy is a well-established and stable technology. It has several advantages compared to fossil fuels and renewable energy. Most important advantages are the availability all over the world (because in every part of the Earth the temperature increases with depth) and the base load. However, a disadvantage is the low energy density compared to, for example, fossil fuels or nuclear energy (Gluyas, et al., 2018).

Geothermal heat is available from different earth layers below the surface of the Netherlands. Different layers exist, which have a corresponding type of geothermal heat. ‘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 (>5000m) is 120 to 140 ºC (Lensink, 2020).

Techno-economic parameters

Techno-economic parameters for an ultra-deep geothermal heat installation with a heat power output to fit the drying process of a regular ceramic plant are stated in Table 10. The expected lifetime of ultra-deep geothermal heat is unknown and therefore assumed to be 25 years. Similar to heat pumps (see subsection 4.3.6) the variable (electricity) O&M costs is no fixed value but adapted from Lensink (2020).

Table 10 Parameters for ultra-deep geothermal, adjusted to fit a regular ceramic plant. Source: adapted from (Lensink, 2020, p. 70).

Parameter	Unit	Value
Power (output) per year	TJ/yr	64[1]
Investment costs (CAPEX)	M€	5,6
O&M costs (fixed OPEX)	M€/yr	0.24
Variable (electricity) O&M costs	€/GJ	2.11[2]

[1] Production * energy required for drying process is 80,000 t * 0.8 GJ/t = 64,000 GJ/yr.
[3] 0.0076 €/kWh / 0.0036 GJ/kWh = 2.11 €/GJ.

4.3.9 Extended tunnel kiln

In 2010, the ceramic industry 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 (30%) when extending a tunnel kiln with an annual production capacity of approximately 80,000 tonnes (TCKI, 2013; TCKI, 2017).

Techno-economic parameters

It is assumed that the lifetime of the extended tunnel kiln technology is the same as the reference fire kiln, which is 30 years. Techno-economic parameters are unknown and therefore only the efficiency improvements of this technology will be analysed.

4.3.10 CO_2 capture and storage (or utilisation)

Carbon capture and storage (CCS), or utilisation (CCU), can be seen as an additional solution to mitigating global climate change, next to increasing energy efficiency, low carbon energy supply and use of terrestrial carbon (Leung, Caramanna, & Maroto-Valer, 2014). Moreover, CCS or CCU is especially applicable to energy intense emitters, such as ceramic plants.

The capture of carbon is currently applicable in three different ways: post-combustion, pre-combustion and oxy-fuel combustion. Each of the three types of technologies has its own advantages and disadvantages, which makes post-combustion best applicable to the ceramic production process. This is because post-combustion is the most mature and can easily retrofit in existing plants. It will therefore have the least impact on the production process. However, a disadvantage of post-combustion is the relatively low concentration of CO_2 in flue gases which makes the technology inefficient (Wilberforce, Baroutaji, Soudan, Al-Alami, & Olabi, 2019). Another advantage, specifically for the ceramic industry, is that by capturing CO_2 emissions post-combustion, process emissions are also included in the capture. The total 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, transport would need to go 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 almost all plants are closely located to big rivers.

Techno-economic parameters

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 as ceramic production plants is very low (<5%). The study provides investment and operational cost values (see Table 11). 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 lifetime of 25 years. 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 (fixed OPEX) and variable cost refer to routine maintenance costs and other fixed variable costs (IEAGHG, 2012, p. 102).

Table 11 Parameters for carbon capture at a gas fired power plant. Source: adapted from (IEAGHG, 2012).

Parameter	Unit	Value (power plant)	Adjusted value (ceramic plant)
CO_2 capture capacity	kt/yr	2500	14
Investment costs (CAPEX)	M€	602	19
O&M costs (fixed OPEX)	€/tCO_2/y	10	10
Variable OPEX	€/tCO_2	4	4
Specific heat consumption	GJ_{th}/tCO_2 captured	3.35	3.35
Specific power consumption	GJ_e/tCO_2 captured	0.58	0.58

The values for the power plant in Table 11 represent a capture unit that is far larger than required for a ceramic plant. Therefore, to realise carbon capture at the size of a ceramic plant, the corresponding numbers are scaled down. This will return feasible techno-economic parameters for a regular sized ceramic plant. Scaling down is performed by a scale factor of 2/3 to include the effect of economies of scale (Blok & Nieuwlaar, 2017). The annual CO_2 emissions number, taken as reference for the ceramic plants, is 14 ktCO_2. This number is the average of all ceramic plants in the Netherlands (including the process emissions). Scaling down results in a CAPEX of 19 M€. The corresponding fixed and variable OPEX, and specific energy consumptions, are assumed to remain constant.

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 in storing 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. According to the SDE++ advice, the current prices for transporting[30] and storing CO_2 are 45 €/tCO_2 and 15 €/tCO_2, respectively (Lensink, 2020, p. 141). Besides storage, utilisation of captured CO_2 might also be a possibility by supplying to greenhouses or the food and beverage sector.

4.4 Concluding on the system analysis

This chapter has provided an overview of the ceramic production processes and shows that three categories of ceramic products can be distinguished: bricks and roof tiles, floor and wall tiles, and refractory products. Bricks and roof tiles are most dominant in the Netherlands, as nearly all ceramic plants produce bricks and/or roof tiles and their production in tonnes covers 96% of the total ceramic production in the Netherlands. This dominance of bricks and roof tiles production also becomes clear from the applied desk research, which results in little literature for bricks and roof tiles, and barely any sources of relevant numbers for the floor and wall tiles and refractory products. Unfortunately no specific case studies could be done at the floor and wall tiles or refractory product plants.

[30] When the CO_2 is transported per boat or road truck, it should be liquefied. This will increase the minimal cost compared to transporting via pipelines.

Showing the difference production numbers between the categories of ceramic products is the first step of answering of *SQ2*, which has been formulated as follows:

"What is the current state of the ceramic sector in terms of processes and CO_2 emissions?"

Consequently, *SQ2* is answered by the mass, energy and CO_2 emission flow diagrams (e.g. Figure 12) for each of the different product categories stated above. These diagrams visualise the results of the input-output analysis and show that the drying and firing processes are the two critical processes, i.e. processes that emit CO_2. Furthermore, the ceramic industry is heavily dependent on the fuel natural gas, which is for the biggest part responsible for the CO_2 emissions output flows. Next to the fuel emissions, up to 26% of the CO_2 emissions follow from chemical reactions during the firing process. Because little data could be collected, assumptions had to be made in calculating the specific CO_2 emissions.

Considering the availability of supply of material and energy, which is neglected by the applied input-output analysis, this is not expected to be a critical part of the process. The required raw material is sufficiently available and all plants are connected to the national natural gas grid in the Netherlands. However, this changes when analysing the decarbonisation options, which has been conducted in the second part of this chapter.

In total eleven decarbonisation options are selected to be applicable to decarbonising the ceramic production process to a certain degree. The different types of decarbonisation can be categorised in the following categories:

- Fuel substitutions;
- Process design (both efficiency increase and substitution);
- Use of residual energy;
- CO2 capture and storage (CCS) or re-use.

Unfortunately, due to the process emissions, no full decarbonisation can be (theoretically) achieved. Moreover the availability and supply of feedstock and renewable fuels becomes a critical parameter for successful implementation of most decarbonisation options. For example, green gas from biogas could be transported to the ceramic plants through the conventional pipelines of the natural gas grid, though it is not yet clear how this green gas will be produced and whether sufficient production is possible. Besides the problem of supply, many of the decarbonisation options are only theoretically available or have not yet been proven on an industrial scale. These options have serious research gaps that first needs to be filled and further development is desired, before a commercial application would be possible in 2030.

The provided overview of the reference technology and decarbonisation options in this chapter will be used for the MAC analysis and BCA, of which the results are stated in the next chapter.

5 Scenario results

This chapter discusses the results of the MAC analysis and BCA, including a sensitivity analysis on different energy prices and discount rates. These results provide an answer to both *SQ3* and *SQ4*, which are stated below. More specifically, *SQ3* will be answered by the MAC analysis, including the construction of MAC curves, and *SQ4* will be answered by both the MAC analysis and BCA.

SQ3: "From a technological perspective, how can the ceramic industry in the Netherlands be decarbonised?"

SQ4: "From an economic perspective, how can the ceramic industry in the Netherlands be decarbonised?"

In total, eleven decarbonisation options have been discussed in the previous chapter. For some options, no detailed information about techno-economic characteristics could be determined. Therefore these options are not further included in the economic analysis because essential cost parameters are missing. Nevertheless, they are included in the MAC analysis if the efficiency improvement is known. These options, included in the technological analysis but excluded from the economic analysis, are: Heat recovery, hybrid drying and the extended tunnel kiln.

Considering the MAC and BCA analysis, the following decarbonisation options are included. More information about their techno-economic characteristics can be found in section 4.3.

- Green gas (digestion): onsite production of green gas through digestion;
- Green gas (gasification): onsite production of green gas through gasification;
- Hydrogen: green hydrogen from the hydrogen grid;
- Electric kiln and drying: Electric heating (exact technology is unknown);
- Heat recovery (only efficiency improvement is known);
- Industrial heat pumps: Heat pumps with a closed system;
- Hybrid drying (only efficiency improvement is known);
- Ultra-deep geothermal: Extracting heat from layers below 4000m;
- Extended tunnel kiln (only efficiency improvement is known);
- CCS: post-combustion capture of CO_2, including transportation and storage costs.

The following sections of this chapter state the results of the MAC analysis and BCA, for which the methodology is discussed in chapter 3. First, section 5.1 states the results of the MAC analysis and construction of MAC curves from a social and private perspective, including a sensitivity analysis. And second, section 5.2 discusses the BCA with the different evaluation parameters. Finally, section 5.3 concludes on the results and provides an answer to *SQ3* and *SQ4*.

5.1 MAC analysis results

The MAC analysis and construction of MAC curves is applied from two perspectives, the social perspective and private perspective. For an explanation of the difference between both perspectives, see subsection 3.3.1. The results of each perspective show an overview of the MACs of all decarbonisation options, which is followed by a discussion of the constructed MAC curve, and finally the sensitivity analysis.

5.1.1 MAC analysis from a social perspective

Table 12 shows the results of the MACs for the decarbonisation technologies, according to the calculation method described in section 3.3. These results are applicable to a regular brick and roof tile plant, with an annual production capacity of 14 kt. No specific results are generated for the floor and wall tile plants or refractory plant, due to a lack of data. Table 12 shows that five out of ten options are applicable to both the drying and firing process and four options (i.e. heat recovery, industrial heat pumps, hybrid drying and ultra-deep geothermal) are only applicable to the drying process. The extended tunnel kiln option is only applicable to the firing process.

It can be seen that no negative MAC is calculated. This means that no decarbonisation options will be preferred over the reference technology in terms of costs. In addition, the maximum reduction potential is given. This reduction potential is fully dependent on the process step(s) to which the decarbonisation option can be implemented. The results show that almost all options only mitigate the fuel emissions (3.6 ktCO_2 for the drying process and 6.8 ktCO_2 for firing process). CCS or CCU is the only exception, because this technology is the only decarbonisation option that is capable of mitigating the process emissions. Not all emissions can be mitigated by CCS or CCU, due to its maximum capture capacity of 90%. For a more detailed description of the decarbonisation options, see section 4.3.

Table 12 MACs of the decarbonisation options form a social perspective.

Decarbonisation option	Relevant process(es)	Maximum reduction potential (ktCO_2)	MAC (€/tCO_2)
Green gas (gasification)	Drying & Firing	10.4	193
Green gas (digestion)	Drying & Firing	10.4	100
Hydrogen	Drying & Firing	10.4	462
Electric kiln and drying	Drying & Firing	10.4	168
Heat recovery	Drying	1.08	*n.d.*
Industrial heat pumps	Drying	3.6	21
Hybrid drying	Drying	0.9	*n.d.*
Ultra-deep geothermal	Drying	3.6	117
Extended tunnel kiln	Firing	2.04	*n.d.*
CCS (or utilisation)	Drying & Firing	12.6[1]	302

[1] Including the capture of process emissions.

Efficiency improvement

As described in section 4.3, for some decarbonisation options no techno-economic parameters could be derived to calculate the MAC. These options can be identified in Table 12 by a *n.d.* for their MAC. However, their increase of efficiency with regards to specific energy consumption per tonne end product could be calculated. Below, the efficiency improvement is analysed for the different ceramic product categories: bricks and roof tiles, floor and wall tiles, and refractory products. The improvement in energy efficiency leads to a reduction of total energy usage. To determine a possible improvement of energy efficiency, the energy input of the decarbonisation option is compared with the energy input of the reference technology. Not all decarbonisation options stated in Table 12 improve the energy efficiency. For example, green gas is only a fuel substitution that has the same input in the process in terms of energy as natural gas.

The energy efficiency improvement options are heat recovery (from flue gases), industrial heat pumps, hybrid drying and the extended tunnel kiln (see Table 13). Two efficiency improvement values are given: first the efficiency improvement of the option compared to the reference technology, and second the efficiency improvement for the production process of bricks and roof tiles. The latter value includes all energy inputs and therefore results in a lower percentage. For all calculation steps of the efficiency increase, see Appendix E.

Table 13 Efficiency improvement parameters. These values are applicable to the manufacturing process of bricks and roof tiles. Source: own calculations.

Decarbonisation option	Relevant process	Efficiency improvement (process step)	Efficiency improvement (whole process)
Heat recovery	Drying	28%	9%
Industrial heat pumps	Drying	75%	24%
Hybrid drying	Drying	25%	8%
Extended tunnel kiln	Firing	30%	18%

Table 13 shows that industrial heat pumps have the highest efficiency improvement, which is a result of using only 25% of the input energy compared to the reference technology (i.e. gas-fired drying). This means an efficiency improvement of 75%. The extended tunnel kiln saves 30% of natural gas use during the firing process. And heat recovery and hybrid drying technologies save 28% (residual heat from flue gases) and 25% (saving natural gas) during the drying process, respectively. Furthermore, some options can substitute each other and therefore are not applicable at the same time. This is the case for heat recovery, industrial heat pumps and hybrid drying. Since the industrial heat pumps technology has the highest efficiency rate of the three options, this technology can best be combined with an extended tunnel kiln, which is applicable to the firing process. When these two technologies are combined and applied to a production process, the total efficiency improvement can be calculated for the different ceramic products.

Figure 18 shows that the biggest improvement can be made for bricks and roof tiles (more than 40%). Refractory products can be improved by 30%, with a bigger impact of the extended tunnel kiln than for bricks and roof tiles. And floor and wall tiles only will have a slight savings of energy due to the fact that the extended tunnel kiln is not applicable to their production process, and the energy required for drying is relatively small compared to the whole production process.

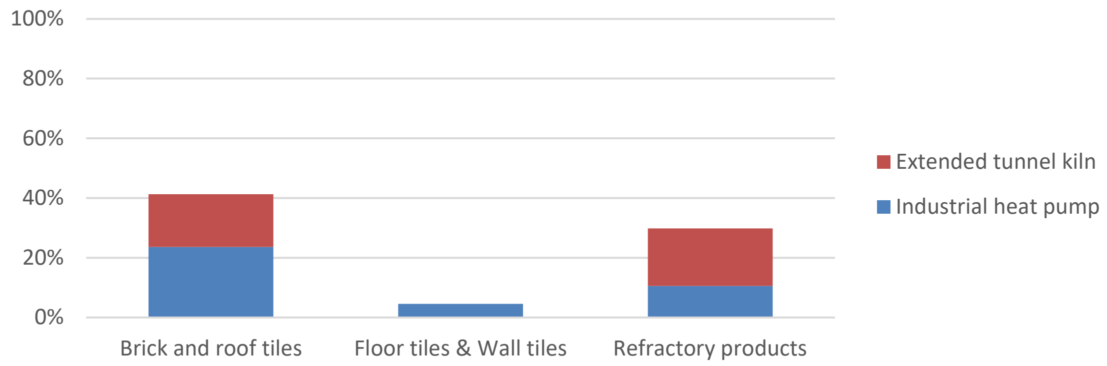


Figure 18. Efficiency improvement for different ceramic products.

5.1.2 MAC curve from a social perspective

The MAC curve from a social perspective is constructed and ordered according to the MACs of the decarbonisation options (see Table 16) and the SEC per process step. Figure 19 shows that the drying process step is decarbonised by heat recovery and heat pumps. The heat recovery option decarbonises by 1.08 ktCO_2 and heat pumps cover the remaining 2.52 ktCO_2 resulting from the drying process of a regular ceramic plant[31]. The firing process of such a plant is decarbonised by an extended tunnel kiln (2.04 ktCO_2) and firing by green gas produced with digestion (8 ktCO_2). Finally, the process emissions are for 90% captured by CCS/CCU (3.2 ktCO_2). Since the MAC of the options heat recovery and extended tunnel kiln cannot be defined, these are given an arbitrarily value of 10 and 15 €/ktCO_2, respectively. In Figure 19 the MAC curves of these options are bordered by a dotted line. The total reduction potential that is achieved is 13.62 ktCO_2 for a regular ceramic plant with a CO_2 emission profile of 14 ktCO_2 per year. This means that more than 97% of the CO_2 emissions could potentially be reduced, however at a considerable cost and still some CO_2 emissions (0.38 ktCO_2) cannot be prevented.

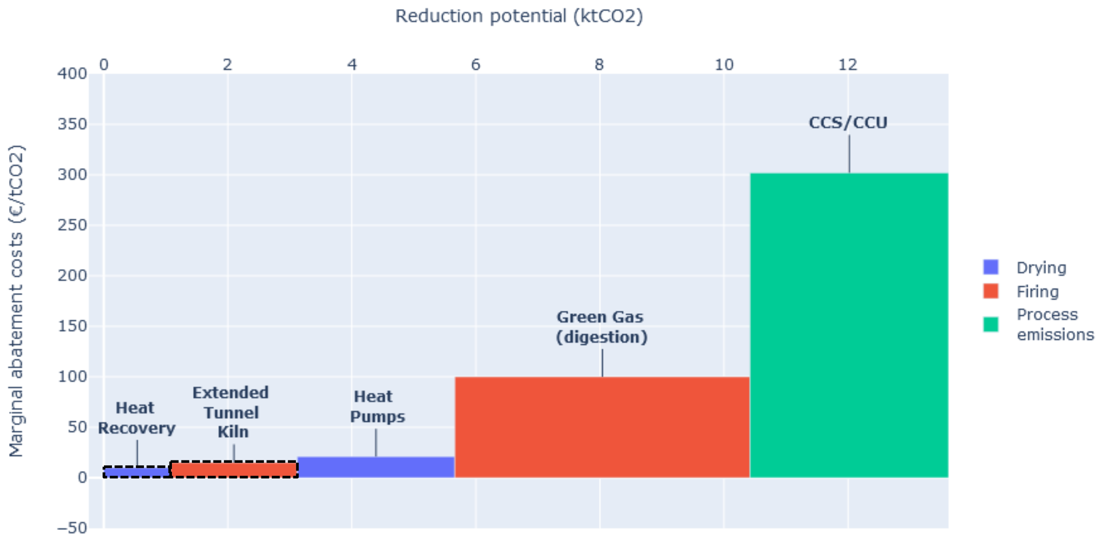


Figure 19. MAC curve of the decarbonisation options from a social perspective.

[31] A regular ceramic plant has a production capacity of 80 kt.

Translating the above results to the whole Dutch ceramic industry would not change the order of options or MACs, since it is assumed that the decarbonisation options are implementable at each plant. However, the total reduction potential would increase (see Table 14). These results are adapted from the constructed MAC curve (see Figure 19).

Table 14 Reduction potential of the decarbonisation options for a regular brick and roof tile plant, and for the whole ceramic industry in the Netherlands. Source: Own calculations.

Decarbonisation option	Reduction potential for one regular plant ($ktCO_2$)	Reduction potential for whole ceramic industry ($ktCO_2$)
Heat recovery	1.08	38.57
Extended tunnel kiln	2.04	72.86
Heat pumps	2.52	90
Green gas (digestion)	4.76	170
CCS/CCU	3.06	109.29
TOTAL	13.46 (96%)	480.72 (96%)

Sensitivity analysis of MAC from a social perspective

A sensitivity analysis is applied to show the impact of the input parameters. This method is conducted by changing the prices of electricity, natural gas and hydrogen independently from each other. This is done independently because change the price of natural gas has a reverse effect on the MAC compared to changing the price of electricity or hydrogen. For example, considering the MAC of industrial heat pumps: increasing the natural gas price would decrease the MAC as a result of a higher variable OPEX of the reference technology. However, increasing the electricity price would increase the MAC as a result of a higher variable OPEX of the industrial heat pumps technology. Combining these two price changes cannot give a clear estimation of the real effect of a price change on the MAC.

First a sensitivity analysis has been applied to determine the effect of increasing and decreasing the fuel prices by 20%, a difference that is chosen to cover the different energy prices mentioned by literature (see subsection 3.3.2). However, this resulted in no significant changes in the order of the MAC curve of the decarbonisation options. Therefore, no these results are not visualised and the prices have been altered to -80% as minimum and +100% as maximum to create a shift in order and find relevant tipping points.

The resulting range of values for the energy prices and discount rate is stated in Table 22 (in Appendix D) and shows that the lowest prices for electricity, natural gas and hydrogen are ranging from 1.50 €/GJ to 30 €/GJ (see Table 15). The highest price for hydrogen is the base input price since this technology already has the highest MAC and increasing this price will have no influence on the order of the MAC curve or cost effectiveness of the hydrogen option. Besides the sensitivity figures of each price change, the corresponding MAC curves of the most optimistic and pessimistic scenario per fuel are also discussed in Appendix D.

Table 15 Minimum and maximum values of fuel prices for the sensitivity analysis. Values are given in €/GJ.

Fuel type	-80%	Base input	+100%
Electricity	3.00	15.00	30.00
Natural gas	1.50	7.50	15.00
Hydrogen	6.00	30.00	x

Figure 20 shows the resulting ranges of MAC for the different decarbonisation options. The maximum and minimum values of MAC of the decarbonisation technologies are derived from Figure 30, Figure 33, Figure 36 and Figure 38, which are explained in detail in Appendix D. The figure shows a number of interesting things. First, the hydrogen is most sensitive which is caused by changing in the hydrogen price. However, even at the lowest price of hydrogen that is included in this analysis (6 €/GJ), the MAC is still positive thus less cost effective than the gas-fired reference technology. In fact, the price of hydrogen should be lower than 4 €/GJ (14.4 €/MWh) to create a negative MAC.

After hydrogen, electric heating becomes second most sensitive to price changes which could result in a MAC that is close to zero or a MAC that might be the least cost effective (when the hydrogen price is low) at a MAC of 380 €/tCO_2. CCS is little sensitive to the price changes and therefore shows that the MAC of that technology is more dependent on the CAPEX and fixed OPEX than the values of energy prices. Furthermore, all technologies' MAC show a significant decrease when the natural gas price is doubles (i.e. increased by 100%). The result of such a natural gas price (15 €/GJ) would result in a negative MAC for three technologies: Industrial heat pumps (-112 €/tCO_2), green gas from onsite digestion (-33 €/tCO_2) and ultra-deep geothermal heat (-11 €/tCO_2).

Last, the effect of changing the discount rate is less than changing the energy prices (see Appendix D). This is an important result, because it shows that a wrongly modelled energy price has more impact than a different discount rate. However, it should also be considered that this discount rate has impact based on the investment costs and lifetime, in contrast to the energy prices that affect the variable OPEX of the decarbonisation option.

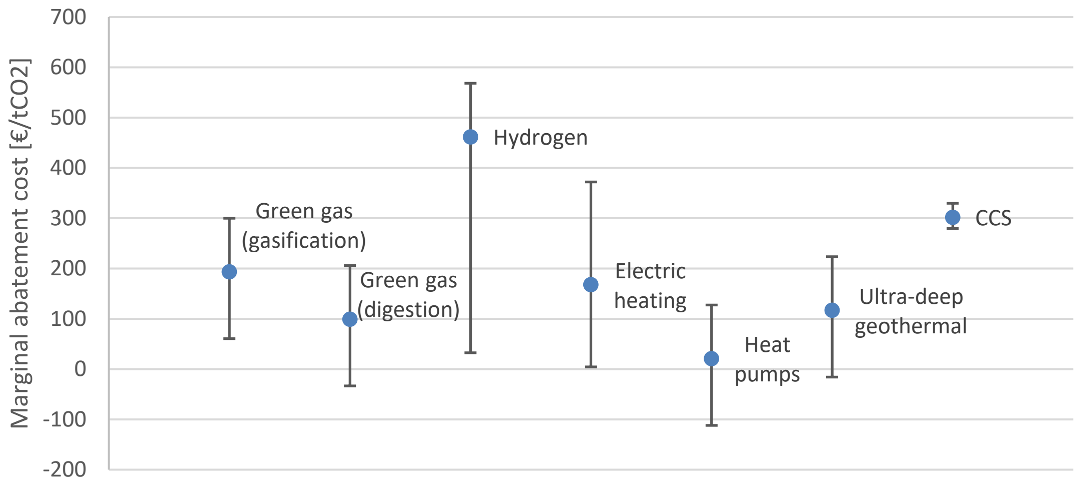


Figure 20. Ranges of MACs of the different decarbonisation options. The blue dots show the MACs for the reference level. Source: own calculations.

5.1.3 MAC analysis from a private perspective

This subsection discusses the results from calculating the MAC and corresponding construction of the MAC curve from a private perspective. An important difference between this private perspective and the social perspective is the higher discount rate (9%) and inclusion of CO_2 taxes (47 €/tCO_2).

As discussed in the theoretical framework and methodological chapter, the private perspective enables a better representation of the market and can therefore be used for investment decisions of the ceramic plant owners. Because two added parameters (i.e. higher discount rate and inclusion of CO_2 taxes) influence the MAC from a private perspective, the calculation of the MAC is given in three steps (see Table 16). First the MAC from a social perspective is given, then effect of a higher discount rate, and third the inclusion of CO_2 taxes. Altogether, this adds up to the MAC from a private perspective.

Table 16 MAC of the decarbonisation options from a private perspective. The effect of a private discount rate, the effect of a CO_2 tax, and the MAC from a private perspective are given. All numbers are given in €/tCO_2.

Decarbonisation option	Social MAC	Discount rate	CO_2 tax	Private MAC
Green gas (gasification)	193	+67	-47	**213**
Green gas (digestion)	100	+21	-47	**74**
Hydrogen	462	+0	-47	**415**
Electric kiln and drying	168	+40	-47	**161**
Heat recovery	*n.d.*			***n.d.***
Industrial heat pumps	21	+23	-47	**-3**
Hybrid drying	*n.d.*			***n.d.***
Ultra-deep geothermal	117	+58	-47	**128**
Extended tunnel kiln	*n.d.*			***n.d.***
CCS (or utilisation)	302	+57	-47	**312**

Table 16 shows that the private MAC is for some decarbonisation options higher than the social MAC and for other options lower. This is caused by the higher discount rate which has significant effect on, for example, green gas from gasification (+67 €/tCO_2) and no effect on hydrogen (due to zero investment costs). The average increase in MAC caused by the change in discount rate is 38 €/tCO_2. As a result, the height of the CO_2 tax determines whether the change from a social discount rate to private discount rate turns out to be economically beneficial for implementing the decarbonisation option. This is further discussed in the sensitivity analysis of the CO_2 tax at the end of the next subsection (see Table 17).

5.1.4 MAC curve from a private perspective

Figure 21 shows the MAC curve that is constructed based on the decarbonisation options' reduction potential and MAC from a private perspective. Comparing the curve to the MAC curve from a social perspective (see Figure 19) shows the same order of technologies with different MACs. Three options have a negative MAC including the options heat recovery and extended tunnel kiln, for which an arbitrary value for the MAC of -15 €/tCO_2 and -10 €/tCO_2 is taken, respectively. The third decarbonisation option with a negative MAC - the only one that is calculated - is heat pumps with a MAC of -3 €/tCO_2. This negative MAC is a first indication that heat pumps are financially more attractive to invest in than the reference gas fired option, and could therefore be preferred over the reference technology. Furthermore, the reduction potential of all options has not changed compared to the MAC curve from a social perspective and since the order of decarbonisation options is similar too, the width of all columns stay the same compared to the MAC curve from a social perspective. This also means that the reduction potential per decarbonisation options for the whole ceramic industry is equal to the values stated in Table 14.

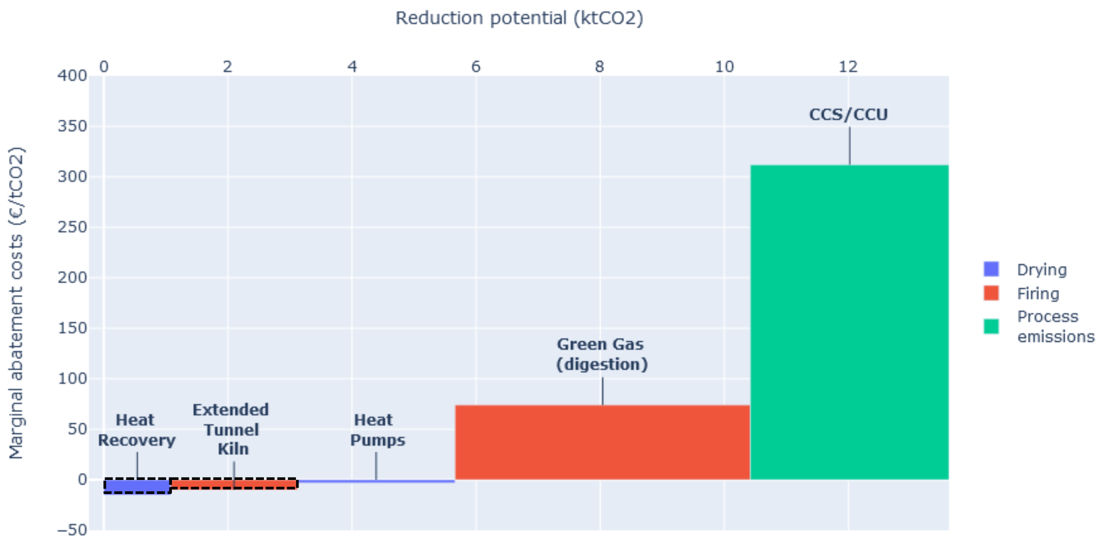


Figure 21. MAC curve of the decarbonisation options from a private perspective.

Sensitivity analysis of MAC from a private perspective

The sensitivity analysis is applied such that it can be determined what the value of the private discount rate or CO_2 should be to make a decarbonisation option financially more attractive to invest in than the reference technology.

Table 17 shows that all options require a present CO_2 tax, and the height of this tax differs per option but shows relatively large numbers in general. Six out of seven options require a CO_2 tax above 100 €/tCO_2 and four of these six options even more than 200 €/tCO_2. Industrial heat pumps require the lowest CO_2 tax and is the only option to which a discount is applicable at all. This means that the other options still have a positive MAC for the lowest possible discount rate. The maximum discount rate for which industrial heat pumps is financially more attractive than the reference technology is 9.6%.

Table 17 Maximum discount rate and minimum CO_2 tax required to prefer the decarbonisation option over the reference technology.

Decarbonisation option	Private MAC [€/tCO_2]	Required discount rate [%]	Required CO_2 tax [€/tCO_2]
Green gas (gasification)	213	-	≥260
Green gas (digestion)	74	-	≥121
Hydrogen	415	-	≥462
Electric kiln and drying	161	-	≥208
Industrial heat pumps	-3	≤9.6	≥44
Ultra-deep geothermal	117	-	≥164
CCS (or utilisation)	302	-	≥349

5.2 BCA results

To apply a BCA, the decarbonisation technologies are compared according to their NPV, PBP and IRR. Table 18 states these parameters for the initial results, with a discount rate of 9% and CO_2 tax of 47 €/tCO_2. The table shows that only the industrial heat pumps options shows a positive NPV, and is therefore the only option that can generate a PBP and IRR. The investment in industrial heat pumps has a positive net present value of almost 85 thousand Euros which is less than 4% of the initial investment cost (2.5 M€). Furthermore, the pay-back-period is 7 years, which is relatively high compared to the lifetime of the technology (12 years) and too high according the required PBP of max 5 years. Finally, the internal rate of return is less than 10%, which might be a barrier to investing.

Table 18 Results of the BCA, including the private MACs and difference with social MACs. Furthermore, the evaluation parameters (NPV, PBP and IRR) are determined if possible.

Decarbonisation option	MAC (€/tCO_2)	Difference social MAC	NPV (€)	PBP (yr)	IRR (%)
Green gas (gasification)	213	+20	-21,761,805	∞	-
Green gas (digestion)	74	-26	-7,584,762	∞	-
Hydrogen	415	-47	-46,315,843	∞	-
Electric kiln and drying	161	-7	-18,026,471	∞	-
Industrial heat pumps	-3	-24	85,685	6.92	9.682
Ultra-deep geothermal	128	+11	-4,552,303	∞	-
CCS (or utilisation)	312	+10	-38,577,776	∞	-

Maximum PBP and minimum IRR

The initial results of the BCA provide little insight, since industrial heat pumps is the only option for which the PBP and IRR can be calculated. As a results, no options can be compared based on their PBP and IRR. Therefore, Table 19 shows the results of what the height of the CO_2 tax theoretically should be to generate a maximum PBP of 5 years and a minimum IRR of 10%. As discussed in subsection 5.1.3, a higher CO_2 tax positively increases the cash flow of the decarbonisation options.

Table 19 CO_2 taxes required per decarbonisation to reach a maximum PBP of 5 years and minimum IRR of 10%.

Decarbonisation option	PBP ≤ 5	IRR ≥ 10%
Green gas (gasification)	≥435	≥277
Green gas (digestion)	≥178	≥127
Hydrogen	≥693	≥592
Electric kiln and drying	≥545	≥341
Industrial heat pumps	≥86	≥49
Ultra-deep geothermal	≥324	≥190
CCS (or utilisation)	≥507	≥428

Table 19 shows that, besides industrial heat pumps, all options require a high CO_2 tax to reach the targets of a maximum PBP and minimum IRR. Furthermore, these results show that some options prefer a maximum PBP of five years over a minimum IRR of 10%. For example, CCS (or CCU) has a relatively low requirement of PBP (≥507) compared to IRR (≥428). The opposite is present for the electric kiln and drying. When these two options are compared, the table shows that CCS (or CCU) is preferred when only looking at the maximum PBP. When only looking at IRR, the electric kiln is preferred over CCS (or CCU). And when taking both the PBP and IRR into account, the CCS (or CCU) will be chosen because it requires a slightly lower CO_2 tax than the electric kiln and dryer (507 €/tCO_2 compared to 545 €/tCO_2).

5.3 Concluding on the results

This chapter has showed and discussed the results of the MAC analysis and BCA, which enables the answering of the last two sub research questions:

SQ3: "From a technological perspective, how can the ceramic industry in the Netherlands be decarbonised?"

SQ4: "From an economic perspective, how can the ceramic industry in the Netherlands be decarbonised?"

Decarbonisation potential from a technological perspective

Starting with *SQ3*, the decarbonisation from a technological perspective can be achieved by the decarbonisation options that are visualised in one of the MAC curve (e.g. see Figure 19). It is not relevant whether a social or private perspective is chosen, because this has no influence on reduction potential of the decarbonisation options. The first two options of the MAC curve are based on an increase in efficiency, i.e. heat recovery and the extended tunnel kiln, which are together responsible for 27% of the total decarbonisation potential. Heat recovery from flue gases makes the drying process more efficient, and the extended tunnel kiln increases the efficiency of the firing process. Furthermore, the industrial heat pumps and green gas from digestion enable decarbonisation of the drying and firing process by replacing the conventional natural gas fired technologies. And finally, CCS or CCU would capture the remaining process emissions flows. Unfortunately, no full decarbonisation is possible due to a small percentage of the process emissions that cannot be captured by the CCS or CCU. In the end, the results show that 96% of total CO_2 can theoretically be reduced by implementation of the decarbonisation options.

Considering the technical implementability, the options; heat recovery, green gas from digestion and CCS or CCU could relatively easy be added to the production process because these options have no direct effect on other technologies or equipment, and do not fill up a considerable amount of space. This would be different for industrial heat pumps and the extended tunnel kiln, for which the implementation requires a change in equipment for the drying process and a significant amount of extra space for the extended tunnel kiln. Another possible limitation could be the state of development and availability of the decarbonisation options (see Table 4).

In the short term, reducing CO_2 emissions of the ceramics production processes could, technically, be achieved through an industrial heat pump, or electric drying. The use of flue gas waste heat for drying, however, has not yet been proven on an industrial scale. These decarbonisation options all have in common that less residual heat is required, which currently comes from the firing process. Therefore, a loss in energy efficiency would be created when this residual heat from the firing section is not used anymore. Extending the tunnel kiln solves this problem, though it is unknown what the exact techno-economic characteristics of this option are and whether any other barriers would be present to implementing this decarbonisation option in the firing process. Finally, technical limitations might be present in the supply of energy. This could be present in the required capacity of the electricity net, which is nearly doubled by when implanting industrial heat pumps (see subsection 4.3.6). Another problem of supply might be the supply of green gas that is required for the firing process, because it is currently uncertain whether enough green gas can be produced (see subsection 4.3.1).

Decarbonisation potential from an economic perspective

Discussing the decarbonisation options from an economic perspective, and therewith answering *SQ4*, the social MAC curve (see Figure 19) can be used to show the decarbonisation potential, because a MAC curve shows the marginal cost in an increasing order. This means that the visualised options are most cost-effective to decarbonise the ceramic industry in the Netherlands. However, several uncertainties and limitations exist. First, due to lack of information or technologies being in a very early phase of development, no economic parameters could be determined for a number of options. This is for example the case with the options heat recovery and extended tunnel kiln. Resulting from this lack of information, the MAC analysis and corresponding MAC curve cannot give clear estimation of the economic feasibility of these decarbonisation options. This also becomes clear from the results of the BCA analysis, from which such options cannot be included.

The difference between the results from a social and private perspective shows that the MAC curve from a private perspective (see Figure 21) generates options that are more cost-effective than the social MAC curve, with one option (industrial heat pumps) having a negative MAC[32]. In other words, from an economic perspective, industrial heat pumps is the only option that is cost-effective compared to the reference technology (including a CO_2 tax of 47 €/tCO_2). Only one decarbonisation option having a negative MAC unfortunately results in a limited BCA (see Table 18). Because all other options are less cost-effective than the reference technology, the NPV stays negative and it becomes impossible to calculate the IRR or PBP. Therefore, the BCA has been approached differently to find the 'tipping point' based on the value of the CO_2 tax for which the IRR becomes at least 10% and the PBP at most 5 years. These results show that even if the CO_2 tax would increase to 200 €/tCO_2, only a few options meet the criteria of the evaluation parameters. From this it can be concluded that there is little space for decarbonisation from an economic perspective. Nevertheless, several assumptions are made in this research that could be proven wrong and other aspects are neglected. An example of such other aspects is the competition or synergy between decarbonisation options. All options are individually assessed in this research and therefore it is unknown whether competition or synergy aspects might decrease the MAC. Both competition and synergy aspects could lower CAPEX and OPEX of the decarbonisation options, which results in a lower MAC that might become cost-effective compared to the reference technology. Finally, no forms of subsidy are included in the research. However this is expected to be coherent with a higher CO_2 tax when assuming that each decarbonisation option receives a subsidy based on its specific CO_2 emissions abatement.

[32] Figure 21 also shows that the decarbonisation options heat recovery and extended tunnel kiln have a negative MAC. However, these MACs are imaginary values only to show the decarbonisation potential.

6 Discussion

This chapter will discuss the methods and results of this thesis. It follows the structure of this thesis and therefore starts with discussing the methodological approach, followed by a discussion of the system analysis results, including the ceramic production processes and overview of decarbonisation options. Furthermore, the results of the MAC analysis are discussed, and lastly the BCA results.

Methodological approach

The methodological framework that is described in the beginning of chapter 3 states the choice of a normative scenario type and a techno-economic perspective. This provides a clear guidance for choosing the correct methods and tools, but it also limits the possibilities of research. Despite the fact that a normative scenario type will provide a direction to the decarbonisation objectives and that the techno-economic approach will be best applicable according to several literature studies, it still could be argued that for example an explorative scenario type would create more relevant results because of the long and uncertain timeframe to 2030 and beyond. Such uncertainty is also stated as one of the important risks that must be considered while following the normative scenario type, which are the input uncertainties and output discrepancies. Those risks are limited in this thesis by applying the sensitivity analysis on different input parameters and by using different methods (i.e. the MAC analysis and BCA) to analyse the output parameters.

By choosing for a techno-economic approach, limitations are present too. These limitations can be summarised as a poor representation of technology inertia, innovation and policy change. The poor representation of policy change is to a certain extent covered by introducing the CO_2 tax. Whereas poor representation of technology inertia and innovation are not covered, because the actual transition from a business-as-usual technology (i.e. using natural gas as fuel) to an innovative technology (e.g. heat recovery from flue gases) is not included in the research of this thesis. Therefore, it could be argued that another perspective, e.g. the socio-technical approach, would cover these limitations, since this approach focuses on transition management and innovation policies.

Another discussion point for the methodological approach is the chosen frozen technology and efficiency reference level, starting from the year 2030. These frozen levels are chosen because it is assumed that the decarbonisation options have a considerable lifetime (conventional ceramic kilns have a lifetime of several decades), due to little information that is available, and because a number of decarbonisation options are still being developed. Therefore, it is expected that including a possibility of technology change or efficiency improvement each year would only add extra assumptions, without having significant impact on the results in this thesis.

Finally, considering the economic part of the techno-economic perspective, the neoclassical economics view is followed. From this neoclassical view, the MAC analysis and BCA can be applied, though this means that in this thesis several transaction costs are neglected and the market failures should be justified by governmental intervention. One of these market failures is the presence of environmental costs resulting from CO_2 emissions. This problem is solved in this thesis by including the CO_2 tax as governmental intervention, however it is not further analysed what those environmental costs exactly are.

System analysis – ceramic manufacturing process

This thesis has analysed the ceramic production processes from a bottom-up approach and by using an input-output analysis. This has resulted in detailed process descriptions of the material and energy flows. However, it could be discussed that the scope is quite limited, since the supply of material and energy to the ceramic plants are assumed to be sufficiently available and therefore are neglected in the MAC analysis and BCA. Another limitation of the bottom-up approach is that no feedback between other industries is present, which could result in less cost-effective results because a possible decrease in costs due to cooperation is not included. An example of such decrease in cost would be sharing the investment in increasing the capacity of an electricity infrastructure. However, due to the remote locations of the ceramic plants, a close cooperation with plants from other industries is not expected to be relevant. Considering the CO_2 emissions that are stated in the input-output analysis (as emission output), only the CO_2 emissions that are emitted during the manufacturing process between the plants' walls are included in the research. The transport of material to and from the plants with possible CO_2 emissions is neglected and not further analysed in this thesis. The CO_2 emissions that are included by the input-output analysis are output flows of the drying and firing processes by fuel combustion (natural gas predominantly). During the firing process, CO_2 emissions (named process emissions in this thesis) are also emitted by chemical reactions. Unfortunately the exact plant-specific values of such process emissions could not be retrieved from the plant owners or industry experts due to confidentiality reasons. Therefore this value is averaged over the whole ceramic industry in the Netherlands, neglecting any difference between products or production techniques. Despite this generalisation, the average numbers have been discussed with experts and plant owners of the ceramic industry, who indicated that the final numbers were more or less correct. Furthermore, it is not expected that variation in these CO_2 emissions and SEC's would have large impact on the results.

Another discussion point related to process emissions is the need for carbon atoms in the firing process to activate the chemical reactions (e.g. sintering). This is among other things discussed in the KNB position paper as one of the barriers to using renewable firing technologies (KNB, 2020). For the current results analysed in this thesis, it would not impose any problems due to the fact that natural gas is substituted by green gas which contains the required carbon atoms. However, considering the implementation of an electric or hydrogen kiln, for example, this might cause problems due to the absence of carbon atoms in the fuel. In that case it should also be analysed what the effect is on the chemical reactions, and whether carbon atoms could be added to the firing process as an extra process step. This could result in additional costs for the options that decarbonise the firing process in the absence of carbon atoms.

System analysis – decarbonisation options

The economically most attractive decarbonisation option, from both the social and private perspective, is industrial heat pumps. However, while large scale industrial heat pumps are applied in, among others, the food sector, they have not been proved on an industrial scale at the temperatures required for the drying processes (>100 °C) of the ceramics industry. The other drying option, i.e. electrical drying, would eliminate on-site emissions from the drying process, but no literature is available about this option, and therefore its applicability is uncertain. Furthermore, the impact on the electric grid could be considerate as the energy consumption would be multiplied by a factor of seven. In comparison, the energy consumption is less than doubled when heat pumps are implemented. Therefore, besides the operational costs of the technologies, the external costs of increasing the capacity of the electricity infrastructure should also be analysed. Such network costs could impose a serious barrier to electrifying the ceramic production process because this will increase the increase the MACs and require higher CO_2 taxes (or subsidies) to become cost effective in the MAC curve or meet the evaluation criteria of the BCA. Nevertheless, electricity-based heat production is by other literature mentioned as most cost-effective technology (Fortes, Simoes, Gouveia, & Seixas, 2019).

CCS or CCU (i.e. post-combustion carbon capture and storage or utilisation) could be applied to capture both the fuel and process emissions. However, 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, makes the capture equipment very expensive. In addition, due to the ceramic plants being located far from CO_2 storage facilities (e.g. 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. These transport and storage values are included in the MAC analysis and BCA of this thesis, and despite the fact that these values are very uncertain, it is not expected that this has impact on the decision-making process as long as the capture equipment stays as expensive as today.

Some of the other identified decarbonisation options are not yet commercially available. For example, electric kilns are currently researched to determine the impact of electric heating 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 of using hydrogen for firing on the end-product requires further research. Moreover, indirect negative effects on NO_x policies could be happening as burning hydrogen would increase the NO_x emissions due to higher flame temperatures (KNB, 2020). Ultra-deep geothermal and extended tunnel kilns have potential 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 this is currently not available via the natural gas grid, green gas could potentially be produced on-site use digestion or gasification technology. However, in the case of green gas production from by digestion, the supply feedstock (i.e. cattle manure in this thesis) should be available from nearby farms to prevent extra infrastructure problems and additional costs. It is stated in subsection 4.3.1 that 100 to 200 farms will be required to supply manure to a ceramic plant. However, it is not clear whether farms are nearby enough to keep the transportation costs as low as possible. A factor that increases this uncertainty is that most of the ceramic plants are located in rural areas and relatively close to each other in the south eastern parts of the Netherlands (see Figure 22). As long as such green gas is not possible from nearby suppliers, green gas would become very costly due to transportation costs (if it is available at all). Resulting from this, an electric kiln could become more cost-effective than green gas.

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. Especially equipment such as firing kilns; once a new one is invested in, it will take twenty to thirty years for a new investment opportunity. Related to this question whether the options are commercially available in 2030, is that this thesis might provide more insight when taking 2040 as starting year. This will ensure more certainty that options are commercially available, the required infrastructure is present and policies (such as CO_2 taxes) are better suited to reach full decarbonisation of the industry. On the other hand, the input assumptions become unsure with a longer timeframe and especially the MAC analysis could become inaccurate due to the exclusion of intertemporal dynamics.

Another important barrier towards decarbonisation is the remote location of most of the ceramic manufacturing plants. As mentioned shortly above, this could result 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. Related to this is the discussion whether green gas should be produced on-site, which is assumed in this thesis. However, it might be more cost efficient to produce the green gas on a large scale (especially if supply of feedstock is difficult for the ceramic plant) and transport the green gas through existing pipelines to the ceramic plant. Finally, it is yet unknown how the hydrogen could be supplied to the ceramic plants and what costs are related to this transport. These different uncertainties when looking at the system from a broader view make the current results one of the possibilities (i.e. assuming that the supply of green gas would be sufficient), and not necessarily the best solution.

MAC analysis

Considering the scenario model and applied calculations for the MAC of each option, it is interesting to note that a higher natural gas price or CO_2 tax decreases the MAC, but the specific cost parameters of the decarbonisation option (in terms of CAPEX and OPEX) are not affected by these changes. Whereas a change in electricity price directly affects these values. This difference is not clearly visualized by the results of the MAC analysis, but is relevant because of the high share of energy cost in the cost price of the product (approx. 30%). This insight shows that the MAC analysis does not provide the whole picture from a techno-economic perspective, but provides a first indication of possible decarbonisation options.

Besides the above example of fuel parameters, for which a sensitivity analysis is applied to show the impact of such assumptions, other parameters are not analysed on their impact. The transparency, and related to that the impact of assumptions, of the calculation method of MACs is one of the most important critical points stated by Kesicki & Ekins (2012). Several input parameters in this thesis of the ceramic industry are not further analysed by a sensitivity analysis. For example, the fixed OPEX is assumed to be 5% of CAPEX when no fixed OPEX is provided in literature. In addition, some decarbonisation options have an unknown lifespan because they are not yet commercially available (on an industrial scale). For these options, the lifespan is assumed to be 25 years. Lastly, the operational hours of each technology and the production process of the ceramic plants is expected to be 8000 hours. When any of these assumptions are altered, for example changing the lifetime into 20 years instead 25 years, this is not expected to result in any critical changes.

The parameters that have been analysed with a sensitivity analysis are the fuel prices and discount rates. Nevertheless, the sensitivity analysis results show that different prices would have little impact on the preferred decarbonisation options and the order of the MAC curve. In fact, only the electricity price shows a considerate shift in options when a lower electricity price is taken. This is important to consider, especially because electricity prices can fluctuate considerably during the year. In the summer, when a lot of electricity is produced, the prices would be lower than during the winter (PBL, et al., 2019). When comparing the range of fuel prices applied in the sensitivity analysis with academic literature, it shows that all prices mentioned in other studies are included in the range of the sensitivity analysis. Therefore, all price scenarios are expected to be included and the individual results of the price changes on the decarbonisation options show the sensitivity for each change.

The sensitivity analysis is also performed on the discount rate, for which different discount rates are discussed in the methodology. However, the sensitivity results show that changing this rate has barely any impact on the order of the MAC curve. Only the MAC of each option is affected, which rises with a higher discount rate and decreases with a lower discount rate. Therefore, it is only important put emphasis on choosing the right discount rate when exact cost figures are needed, or when two options are compared of which one has relatively low investment costs and the other has very high investment costs.

Furthermore, another critical note of Kesicki & Ekins (2012) considering the analysis of MAC curves is the focus on individual technologies and not taking into account any competiveness (or synergy) between technologies. For instance, an extended tunnel kiln would only be a good option for making the firing process more energy efficient when a renewable technology for the drying process (not using the residual heat from the cooling down section) is implemented at the same time. Another positive aspect of competitiveness could be lower costs when the owners of concurring decarbonisation options want to increase their market share. This could result in more cost-efficient decarbonisation options that are more cost-effective than the business-as-usual options. Lastly, two limitations of the MAC analysis are the exclusion of intertemporal dynamics and behavioural changes. The exclusion of intertemporal dynamics is similar to the frozen technology and efficiency rate, which is already discussed above, and behavioural changes are not expected to have impact on the results because the results show that little human interaction is present during the ceramic production processes.

BCA

The BCA is similar to the MAC analysis by following the neoclassical economics view, and therefore the limitations corresponding with this neoclassical view have been discussed above. Another point of discussion for the BCA is the point that investments are generally irreversible and therefore testing on a large scale is not possible. As a result, business risks are present that cannot be quantified but have their influence on the attractiveness of the investment. This is related to another limitation of BCA, because this method demands that everything is monetized and aggregated to the present time. This limitation is solved in this thesis by using a discount rate that is based on the WACC. This WACC is – shortly explained – based on the amount of debt and equity of the company for which it has to pay a certain interest rate and would like to receive a rate of return, respectively. However, this WACC would be different for each of the ceramic plants and therefore result in a different discount rate for the MAC calculations and BCA. Nevertheless, it is already explained above that a different discount rate has little impact on the results, and therefore it is not expected to be a significant simplification of the analysis.

Three evaluation parameters have been used in this thesis: the NPV, IRR and PBP. Unfortunately, no concrete evaluation was possible as only one option (i.e. industrial heat pumps) turned out to be cost-effective. Nevertheless, some limitations of the three evaluation parameters can be discussed. Starting with the NPV, it is stated that specific preferences could exist, such as preferring a large cash flow in the first few years over the height of the NPV. Translating this limitation to the research in this thesis would mean that a very low OPEX is preferred over the height of the CAPEX, which would make industrial heat pumps even more a preferred option because its OPEX (56,000 €) is only 2.3% of its CAPEX (2.5 M€). The IRR is not influenced by the CAPEX, however the required value of the IRR is unclear because this was considered confidential information by the ceramic plant owners. This thesis has applied an IRR of 10% which is relatively low compared to literature, however the results still show that for most decarbonisation options a considerable CO_2 tax is required to meet this requirement of 10%. Finally, the pay-back-period is the most straightforward parameter and easiest to determine. Despite its simplicity, the added value of the PBP is that does not require the discount rate to be calculated. The results of the BCA show that the required maximum of 5 years for the PBP is a strict evaluation compared to the IRR of 10%. This could mean that plants indeed apply a higher minimum value of IRR to evaluate investment options.

7 Conclusion

This thesis has applied a techno-economic analysis on the ceramic industry to determine which technologies and to what extent these technologies could mitigate the current CO_2 emissions of the ceramic industry in the Netherlands. The main research question has been formulated similar to this as follows:

"Following a techno-economic perspective, how can the ceramic industry in the Netherlands decarbonise their manufacturing processes?"

The answer to the main research question is introduced by each of the concluding sections of previous chapters that have provided answers to the four sub research questions. *SQ1* is answered by showing that a normative scenario type, including a bottom-up approach to describe the ceramic industry. And a neoclassical economics view accompanied by the MAC analysis and BCA answers best to the techno-economic perspective.

SQ2 shows that three product categories can be distinguished in the Netherlands: bricks and roof tiles, floor and wall tiles, and refractory products. Furthermore, the total specific CO_2 emissions of ceramic products range from 0.18 to 0.48 tCO_2 per tonne end product, and the critical processes that emit CO_2 are the drying and firing section. Several decarbonisation options are listed that applicable the decarbonising these two process steps, categorised as an increase in efficiency, fuel substitution, process substitution, residual energy recovery and carbon capture.

SQ3 and *SQ4* answer the question how the ceramic industry can be decarbonised from a technical and economic perspective. In total eleven decarbonisation options could be applied to the ceramic manufacturing process in the Netherlands in 2030. In theory, a combination of these options could decarbonise the process for more than 90% of which the remaining emissions can all be related to process emissions resulting from chemical reactions during the firing process. However, from a technical perspective, important parameters could not be defined or are uncertain for decarbonisation options like heat recovery and the extended tunnel kiln. More importantly, from an economic perspective only industrial heat pumps are economically feasible with a MAC of -3 €/tCO_2, a NPV of 86,000 €, IRR of 9.6% and PBP of 7 years. This results is from a private perspective, thus including a CO_2 tax of 47 €/tCO_2. All other options would require substantially higher CO_2 tax (>120 €/CO_2) to be economically feasible in 2030.

This shows that there is little perspective on decarbonisation for the ceramic industry in 2030, something that is also confirmed by the branch organisation KNB. Nevertheless, many research is conducted by the branch organisation KNB and knowledge institutes at the moment and will provide new insights on decarbonisation technologies like the electric kiln in the coming years.

Taking everything into account, and therewith answering the main research question, it is concluded that the ceramic industry in the Netherlands can decarbonise their production process by implementing industrial heat pumps (the only technology that is applicable both from a technical and economic perspective), which will decarbonise the process by 26% but decreases the energy efficiency of the whole process. This decarbonisation percentage could rise to 40% when heat recovery from flue gases and the extended tunnel kiln turn out to be applicable too, however this could not be verified in this research due to missing cost numbers. Considering CO_2 emissions related to the high temperature firing process, green gas from onsite digestion is the most attractive decarbonisation option based on the technical results, however this option will not be cost-effective and possible barriers exist considering the supply or production of green gas. And last, the process emissions could technically be captured by CCS or CCU, however this will neither be economically feasible, and transport and storage or utilisation must be possible.

Recommendations for further research

From the discussion (see chapter 6), it follows that a number of critical notes require further research and still some knowledge gaps are present. The main recommendation for further research is applying a different perspective, as stated by Cherp, et al. (2018), which would be a more social-technical perspective. This different perspective enables the creation of a more innovative picture of the ceramic industry, including policies and therewith broadening the system.

Furthermore, further research could include a specific case study of a single ceramic plant, to analyse more in detail the specific techno-economic parameters of the plant and the related BCA. The exact WACC, and resulting from that a specific discount rate, could be determined and three (or more) evaluation parameters personally suited to the case study. Moreover, the firing process could be analysed more in detail to determine the best suitable decarbonisation option. This will also provide an answer how to get carbon atoms in the firing process. Finally, the surrounding infrastructure of the plant can be analysed in detail to determine critical supply chains.

A last recommendation for further research is concentrating on a few decarbonisation options that are best applicable to a specific production process of the ceramic industry. This will enable more detailed calculations from a technical perspective on the process characteristics. And the corresponding decarbonisation options could be analysed more in depth to provide a more detailed and industry specific analysis including an extensive and more variable model.

References

Albino, V., Izzo, C., & Kühtz, S. (2002). Input–output models for the analysis of a local/global supply chain. *International Journal of Production Economics, 78*(2), 119-131.

Altenburg, M. (2020). Cost-effectiveness of decarbonisation options for the vegetable oil and fat industry in the Netherlands.

Amer, M., Daim, T. U., & Jetter, A. (2013). A review of scenario planning. *Futures, 46*, 23-40.

Axelos. (2017). *Managing Successful Projects with PRINCE2®.*

Ball, M., Wietschel, M., & Rentz, O. (2007). Integration of a hydrogen economy into the German energy system: an optimising modelling approach. *International Journal of Hydrogen Energy*, 1355-1368.

Bedrijvenmonitor. (2020). *B.V. Steenfabriek Huissenswaard.* Retrieved from https://bedrijvenmonitor.info/bedrijf/industrie/b-v-steenfabriek-huissenswaard/kvknummer/091513130000

Bique, A. O., & Zondervan, E. (2018). An outlook towards hydrogen supply chain networks in 2050 — Design of novel fuel infrastructures in Germany. *Chemical Engineering Research and Design*, 90-103.

Blok, K., & Nieuwlaar, E. (2017). *Introduction to energy analysis - Second edition.* Routledge.

BMI Group. (2017). *Annual Report 2016.*

Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2012). Cost-Benefit-Analysis: Concepts and Practice.

Bohringer, C., & Rutherford, T. (2008). Combining bottom-up and top-down. *Energy Economics, 30(2)*, 574–596.

Bolderdijk, J. W., & Steg, L. (2015). Promoting sustainable consumption: the risks of using financial incentives. *Handbook of Research on Sustainable Consumption,*, 328–342.

Boonekamp, P. (2006). Evaluation of methods used to determine realized energy savings. *Energy Policy*.

Börjeson, L., Höjer, M., Dreborg, K., Ekvall, T., & Finnveden, G. (2006, 9 1). Scenario types and techniques: Towards a user's guide. *Futures, 38*(7), 723-739.

Bouwkroniek. (2018). *Mosa fabriceert 3000 verschillende soorten vloer en wandtegels.* Retrieved from https://www.bouwkroniek.be/article/mosa-fabriceert-3-000-verschillende-soorten-vloer-en-wandtegels.19694

Bouwtotaal. (2019, November 5). *Eerbetoon aan het Nederlandse daklandschap.* Retrieved from Bouwtotaal.nl: https://www.bouwtotaal.nl/2019/11/eerbetoon-aan-het-nederlandse-dakenlandschap/

Brabants Dagblad. (2008, February 2). *Moderniseren is must voor steenfabriek De Rijswaard.* Retrieved from https://www.bd.nl/den-bosch-vught/moderniseren-is-must-voor-steenfabriek-de-rijswaard~acd7fefb/

Brabants Dagblad. (2018, May 19). *Megaproject: In Hedikhuizen hoeven ze hun zonnepanelen niet terug te verdienen.* Retrieved from https://www.bd.nl/heusden/megaproject-in-hedikhuizen-hoeven-ze-hun-zonnepanelen-niet-terug-te-verdienen~acdb0679/

Brynolf, S., Taljegard, M., Grahn, M., & Hansson, J. (2018). Electrofuels for the transport sector: A review of production costs. *Renewable and Sustainable Energy Reviews*, 1887-1905.

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., & Hallett, J. P. (2018). Carbon capture and storage (CCS): the way forward. *Energy & Environmental Science*, 1062-1176.

Campos, J., Serebrisky, T., & Suarez-Aleman, A. (2016). *Time Goes by: Recent Developments on the Theory and Practice of the Discount Rate.*

Caprice Holding B.V. (2020). *History.* Retrieved from https://capricebaksteen.nl/over-ons/historie

Caprice Holding B.V. (2020). *Productieproces.* Retrieved from https://capricebaksteen.nl/over-ons/productieproces

Cardoso, J., Silva, V., & Eusébio, D. (2019). Techno-economic analysis of a biomass gasification power plant dealing with forestry residues blends for electricity production in Portugal. *Journal of Cleaner Production*, 741-753.

CBS. (2020, June 30). *Dierlijke mest; productie en mineralenuitscheiding, diercategorie, regio.* Retrieved from CBS Statline: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83982NED/table?dl=EC0A

Cerame Unie. (2012). Ceramic Industry Roadmap: Paving the way to 2050.

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., Sovacool, B., & . (2018). Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Research & Social Science*, 175-190.

Chiuta, S., Engelbrecht, N., Human, G., & Bessarabov, D. (2016). Techno-economic assessment of power-to-methane and power-to-syngas business models for sustainable carbon dioxide utilization in coal-to-liquid facilities. *Journal of CO2 Utilization*, 399-411.

Clarke, L., & Jiang, K. (2014). Assessing Transformation pathways.

Cobouw. (2010). *Caprice in baksteen op solotoer.* Retrieved from https://www.cobouw.nl/bouwbreed/nieuws/2010/03/caprice-in-baksteen-op-solotoer-101125505

Cobouw. (2018, June 28). *Hoe twee buitenlandse partijen vechten om de lucratieve Nederlandse bakstenenmarkt.* Retrieved from https://www.cobouw.nl/bouwbreed/nieuws/2018/06/hoe-twee-buitenlandse-partijen-vechten-om-de-lucratieve-nederlandse-bakstenenmark-101262431

Correljé, A. F., & Groenewegen, J. P. (2009). Public values in the energy sector: economic perspectives. *International Journal of Public Policy*, 395-413.

Correljé, A., & van der Linde, G. (2006). Oil and gas supply security and geopolitics. *Energy Policy, 34*, 532–543.

Correljé, A., Van der Linde, C., & Westerwoudt, T. (2003). *Natural gas in the Netherlands. From cooperation to competition?*

Corten, J. (1994). *PIE Rapportenreeks 7 - Grofkeramische Industrie.* Retrieved from https://www.industrieel-erfgoed.nl/sites/default/files/bijlagen/bestanden/pie_rapport_07_grofkeramische_industrie.pdf

Dascalaki, E. G., Balaras, C. A., Kontoyiannidis, S., & Droutsa, K. G. (2016). Modeling energy refurbishment scenarios for the Hellenic residential building stock towards the 2020 & 2030 targets. *Energy and Buildings*, 74-90.

DOWN TO EARTH BV. (2013). *Integrale aanpak warmte steenfabrieken, onderdeel besturen.* Retrieved from https://www.downtoearth.nl/resources/Warmtevraagbeperking-in-de-keramische-industrie.pdf

Dutch emissions authority. (2020). *Emissiecijfers 2013-2019. .*

E4tech. (2015). *Scenarios for deployment of hydrogen in contributing to meeting carbon budgets.*

EC. (2007). *BREF for ceramic manufacturing industry.*

EC. (2007). *Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry.*

ECN & DNV GL. (2016). *Eindadvies basisbedragen SDE+.* Petten.

Ecofys. (2006). *Omzetting van rejects uit de papier en kartonindustrie naar energie op eigen terrein.*

Ecofys. (2009). *Methodology for the free allocation of emission allowances in the U ETS post 2012 - ceramics.*

Ecosys. (2014). *Vandersanden Steenfabrieken NV - Aanvraag tot ontheffing MER-plicht in kader van een milieuvergunningsaanvraag tot het bekomen van een hernieuwing van.*

Edelenbosch, O., Kermeli, K., Crijns-Graus, W., Worrell, E., Bibas, R., & Fais, B. (2017). Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. *Energy*, 701-710.

Element Energy. (2018). *Industrial Fuel Switching Market Engagement Study.*

Eliche-Quesada, D., & al., e. (2017). Comparative study of the use of different biomass bottom ash in the manufacture of ceramic bricks. *Journal of Materials in Civil Engineering*.

Elzenga, H., & Lensink, S. (2019). *Conceptadvies SDE++ CO2-reducerende opties: Grootschalige waterstofproductie via elektrolyse.*

Engels Baksteen. (2017). *Bricklopedia.*

Engels Baksteen. (2020). *Productieproces.* Retrieved from https://www.baksteen.nl/engels-baksteen/test-4/

EU. (2016). *Sustainable energy handbook - module 6.1 simplified financial models.*

Euro-Steenhandel B.V. (2020). *Home.* Retrieved from https://www.eurosteen.nl/

Euro-Steenhandel B.V. (2020). *MVO.* Retrieved from https://www.eurosteen.nl/mvo

Finnveden, G., & Moberg, Å. (2005). Environmental systems analysis tools – an overview. *Journal of Cleaner Production, 13*(12), 1165-1173.

Fortes, P., Alvarenga, A., Seixas, J., & Rodrigues, S. (2015). Long-term energy scenarios: Bridging the gap between socio-economic storylines and energy modeling. *Technological Forecasting and Social Change, 91*, 161-178.

Fortes, P., Simoes, S. G., Gouveia, J. P., & Seixas, J. (2019). Electricity, the silver bullet for the deep decarbonisation of the energy system? Cost-effectiveness analysis for Portugal. *Applied Energy*, 292-303.

Freixas, X., & Rochet, J.-C. (1999). *Microeconomics of Banking* (4 ed.). Boston: Massachusetts Institute of Technology.

Gasunie. (2018). *Verkenning 2050 - Discussiestuk.*

Geels, F. W., Schwanen, T., Sorrell, S., Jenkins, K., & Sovacool, B. K. (2018). Reducing energy demand through low carbon innovation: A sociotechnical transitions perspective and thirteen research debates. *Energy Research & Social Science*, 23-35.

Gelderlander. (2018, June 13). *Daas Baksteen uit Azewijn overgenomen door Oostenrijks bedrijf.* Retrieved from https://www.gelderlander.nl/montferland/daas-baksteen-uit-azewijn-overgenomen-door-oostenrijks-bedrijf~a624f534/

Gemeente Heusden. (2019). *Samenwerkingsovereenkomst met Hedikhuizen Duurzaam, gericht op energietransitie.* Retrieved from https://www.heusden.nl/BIS/Vergaderingen/Collegevergaderingen/Besluitenlijst_01_oktober_2019/Samenwerkingsovereenkomst_met_Hedikhuizen_Duurzaam_gericht_op_energietransitie/Samenwerkingsovereenkomst_met_Hedikhuizen_Duurzaam_gericht_op_energietransitie

Gluyas, J. G., Adams, C. A., Busby, J. P., Craig, J., Hirst, C., & Manning, D. A. (2018). Keeping warm: A review of deep geothermal potential of the UK. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 115-126.

Goel, G., & Kalamdhad, A. (2017). An investigation on use of paper mill sludge in brick manufacturing. *Construction and Building Materials*, 334-343.

Gouda Refractories B.V. (2017). *Into Business Coverstory.*

Gouda Refractories B.V. (2018). *Uitbreiding Gouda Refractories.* Retrieved from https://www.goudarefractories.nl/nl/nieuws/2018/uitbreiding-gouda-refractories/

Gouda Refractories B.V. (2020). *History.* Retrieved from https://www.goudarefractories.com/en/profile/history/
Gouda Refractories B.V. (2020). *Vacature Plant Manager.* Retrieved from https://www.goudarefractories.nl/nl/vacatures/plant-manager---offline/
Graydongo. (2020). *Rodruza B.V.* Retrieved from https://www.graydongo.nl/nl/overig-rodruza-bv-nijmegen-10030798
Groenewegen, J. (2004). Inzichten uit de institutionele economie: Over vraagstukken van organisatie. *Management Accounting*, 515 – 523.
Guanche, R., de Andrés, A., Simal, P., Vidal, C., & Losada, I. (2014). Uncertainty analysis of wave energy farms financial indicators. *Renewable Energy*, 570-580.
Hansjürgens, B. (2004). Economic valuation through cost-benefit analysis – possibilities and limitations. *Toxicology, 205*(3), 241-252.
Hasegawa, S., Kinoshita, Y., Yamada, T., Inoue, M., & Bracke, S. (2018). Disassembly reuse part selection for recovery rate and cost with lifetime analysis. *International Journal of Automation Technology*, 822-832.
Hazeu, C. (2007). *Institutionele Economie.* Coutinho.
HeatMatrix. (2017). *Test en Validatie van HeatMatrix technologie voor de (grof) keramische industrie.*
Horvath, S., Fasihi, M., & Breyer, C. (2018). Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040. *Energy Conversion and Management*, 230-241.
Ibáñez-Forés, V., Bovea, M., & Azapagic, A. (2013, 7 15). Assessing the sustainability of Best Available Techniques (BAT): Methodology and application in the ceramic tiles industry. *Journal of Cleaner Production, 51*, 162-176.
Ibn-Mohammed, T., Randall, C. A., Mustapha, K. B., Guo, J., Walker, J., Berbano, S., & Reaney, I. M. (2019). Decarbonising ceramic manufacturing: A techno-economic analysis of energy efficient sintering technologies in the functional materials sector. *Journal of the European Ceramic Society*, 5213-5235.
Icopal. (2017, 4 3). *Standard Industries voltooit aankoop van Braas Monier en wordt wereldleider in dakbedekking.* Retrieved from http://www.icopal.nl/nieuws/archief/nieuws-2017/standard-industries-voltooit-aankoop-braas-monier.aspx
IEA. (2017). *Techno-economic evaluation of SMR based standalone (merchant) hydrogen plant with CCS.*
IEA. (2019). *The future of Hydrogen: Seizing today's opportunities.*
IEAGHG. (2012). *CO2 capture at gas fired power plants.*
IEE. (2007). *Energy saving concepts for the European ceramic industry.* Retrieved from http://www.ceramin.eu/downloads/D7_Tutorial_Energy_saving_UK.pdf
IRENA. (2015). Smart grids and renewables - A cost benefit analysis guide for developing countries.
Kampman, B., Leguijt, C., Scholten, T., Tallat-Kelpsaite, J., Bru¨ckmann, R., & Maroulis, G. (2016). *Optimal use of biogas from waste streams - An assessment of the potential of biogas from digestion in the EU beyond 2020.* European Commission. Retrieved from Kampman, B., Leguijt, C., Scholten, T., Tallat-Kelpsaite, J., Bru¨ckmann, R., Maroulis, G.,
Kazmi, S., Munir, M., Wu, Y.-F., Hanif, A., & Patnaikuni, I. (2018). Thermal performance evaluation of eco-friendly bricks incorporating waste glass sludge. *Journal of Cleaner Production*, 1867-1880.
Kermeli, K., Edelenbosch, O., Crijns-Graus, W., Ruijven, B. J., Mima, S., Vuuren, D. P., & Worrell, E. (2019). The scope for better industry representation in long-term energy models: Modeling the cement industry,. *Applied Energy*, 964-985.
Kesicki, F., & Ekins, P. (2012). *Marginal abatement cost curves: a call for caution.* Climate Policy.

Kesicki, F., & Strachan, N. (2011). Marginal abatement cost (MAC) curves: Confronting theory and practice. *Environmental Science & Policy*.

Keys, A. (2019). 2050 Decarbonisation of the Dutch Steelmaking Industry.

Klimaatakkoord. (2019). *Klimaatakkoord.* Den Haag.

KNB. (2017). *Productspecificatie metselbaksteen.*

KNB. (2018). *Jaarverslag 2018.*

KNB. (2020). *Brancheorganisatie voor de keramische industrie*. Retrieved from https://www.knb-keramiek.nl/organisatie/

KNB. (2020). *Position paper bij wetsvoorstel nationale CO2 heffing.*

KNB. (2020, October). *Technology Roadmap Bouwkeramiek 2030.* Retrieved from https://www.knb-keramiek.nl/media/268410/knb_tr_ontwerp_dig.pdf

KNB. (2020). *Terugdringing emissies.* Retrieved from https://www.knb-keramiek.nl/themas/duurzaamheid/duurzaam-productieproces/terugdringing-emissies/

KNB. (2020a, June 11). *Pers*. Retrieved from https://www.knb-keramiek.nl/: https://www.knb-keramiek.nl/pers/

Koninklijke Mosa B.V. (2017). *Duurzaamheidsverslag 2015-2016.*

Kriegler, E., Riahi, K., Bauer, N., Schwanitz, V. J., Petermann, N., Bosetti, V., . . . Tho, M. H.-C. (2015). Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change*, 24-44.

Krupa, J., & Harvey, L. (2017). Renewable electricity finance in the United States: a state-of-the-art review. *Energy*, 913-929.

Kuckshinrichs, W., & Koj, J. C. (2018). Levelized cost of energy from private and social perspectives: The case of improved alkaline water electrolysis. *Journal of Cleaner Production*, 619-632.

Kuramochi, T. (2016). Assessment of midterm CO2 emissions reduction potential in the iron and steel industry: a case of Japan. *Journal of Cleaner Production*, 81-97.

L1mburg. (2017, 11 27). *L1NWS: Toeleveranciers bouw durven weer te investeren.* Retrieved from https://l1.nl/l1nws-toeleveranciers-bouw-durven-weer-te-investeren-133620/

Ledda, C., Schievano, A., Scaglia, B., Rossoni, M., Fernández, F. G., & Adani, F. (2016). Integration of microalgae production with anaerobic digestion of dairy cattle manure: an overall mass and energy balance of the process. *Journal of Cleaner Production*, 103-112.

Leicher, J., Giese, A., Al-Halbouni, A., & Görner, K. (2016). Utilization of biogas to provide process heat for industrial manufacturing processes. *European Biomass Conference and Exhibition Proceedings*, (pp. 1635-1641).

Lensink, S. (2020). *Eindadvies Basisbedragen SDE++ 2020.*

Leung, D. Y., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*, 426-443.

Lintsen, H. W. (1993). *Geschiedenis van de techniek in Nederland. De wording van een moderne samenleving 1800-1890. Deel III. Textiel. Gas, licht en elektriciteit. Bouw.* Zutphen: Walburg Pers.

Maier, H., Guillaume, J., van Delden, H., Riddell, G., Haasnoot, M., & Kwakkel, J. (2016, 7 1). An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environmental Modelling and Software, 81*, 154-164.

Markandya, A., Sampedro, J., Smith, S., Dingenen, R. v., Pizarro-Irizar, C., Arto, I., & Gonzalez-Eguino, M. (2018). Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. *Lancet Planet Health, 2*, 126-133.

Mathioulakis, E., Panaras, G., & Belessiotis, V. (2013). Cost-benefit analysis of renewable energy systems under uncertainties. *16th International Congress of Metrology.*

Mechler, R. (2016). Reviewing estimates of the economic efficiency of disaster risk management: opportunities and limitations of using risk-based cost–benefit analysis. *Natural Hazards*(81(3)), 2121-2147.

Meier, A. (1982). *Supply Curves of Conserved Energy.* Lawrence Berkeley Laboratory.

Monfort, E., Mezquita, A., Granel, R., Vaquer, E., Escrig, A., Miralles, A., & Zaera, V. (2010). Analysis of energy consumption and carbon dioxide emissions in ceramic tile manufacture. *Boletin de la Sociedad Espanola de Ceramica y Vidrio, 49*(4), 303-310.

Monier B.V. (2020). *Organisatie.* Retrieved from https://www.monier.nl/over-bmi-monier/organisatie

Moore, M. A., Boardman, A. E., Vining, A. R., Weimer, D. L., & Greenberg, D. H. (2004). "Just give me a number!" Practical values for the social discount rate. *Journal of Policy Analysis and Management*, 789-812.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Vuuren, D. P., . . . Weyant, J. P. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, 747-756.

Nauclér, T., & Enkvist, P.-A. (2009). *Pathways to a Low-carbon Economy.* McKinsey & Company.

Nea. (2020). *Deelnemers ETS*. Retrieved from https://www.emissieautoriteit.nl/onderwerpen/deelnemers-ets

Nea. (2020). *Emissiecijfers 2013-2019.*

Ondraczek, J., Komendantova, N., & Patt, A. (2015). WACC the dog: The effect of financing costs on the levelized cost of solar PV power. *Renewable Energy*, 888-898.

Papadogeorgos, I. (2019). Decarbonisation of the Dutch Container Glass Industry by 2050: A Model-based Analysis of Technology Options.

PB & DNVGL. (2015). *Industrial decarbonisation and energy efficiency roadmaps to 2050 - ceramic sector.*

PBL, et al. (2019). *Klimaat- en Energieverkenning 2019.* Den Haag.

Peet, G. v., Leenstra, F., Vermeij, I., Bondt, N., Puister, L., & Os, J. v. (2018). *Feiten en cijfers over de Nederlandse veehouderijsectoren 2018.* Wageningen Livestock Research. Retrieved from https://edepot.wur.nl/464128

Peng, J., Zhao, Y., Jiao, L., Zheng, W., & Zeng, L. (2012). CO2 Emission Calculation and Reduction Options in Ceramic Tile Manufacture-The Foshan Case. *Energy Procedia. 16*, pp. 467-476. Elsevier Ltd.

Peters, M., Schmidt, T., Wiederkehr, D., & Schneider, M. (2011). Shedding light on solar technologies—A techno-economic assessment and its policy implications. *Energy Policy*, 6422-6439.

Provincie Gelderland. (2015). *Verlenen vergunning Steenfabriek Spijk - Ontwerpbesluit.* Retrieved from https://repository.officiele-overheidspublicaties.nl/externebijlagen/exb-2015-30507/1/Bijlage/exb-2015-30507.pdf

PWC & Fraunhofer. (2014). *Ecodesign prepatatory study on steam boilers.*

Remer, D., Stokdyk, S., & Van Driel, M. (1993). Survey of project evaluation techniques currently used in industry. *International Journal of Production Economics*, 103-115.

Rodruza B.V. (2020). *De kracht van keramiek.* Retrieved from https://www.rodruza.nl/nl/living-bricks/de-kracht-van-keramiek/

Rogers, P., Bhatia, R., & Huber, A. (1998). Water as a Social and Economic Good: How to put the.

Roxburgh, C. (2009). *The use and abuse of scenarios.* McKinsey & Company.

RTV Noord. (2018, September 20). *Steenfabriek Strating kan groei amper aan na moeilijkste periode ooit .* Retrieved from https://www.rtvnoord.nl/nieuws/199073/Steenfabriek-Strating-kan-groei-amper-aan-na-moeilijkste-periode-ooit

RVO. (2016). *MJA3-Sectorrapport Grofkeramische industrie 2015.*

RVO. (2017). *The Netherlands list of fuels version January 2017.*

RVO. (2019). *Energiebesparingsplicht.* Retrieved from https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/energie-besparen/informatieplicht-energiebesparing/energiebesparingsplicht

RVO. (2019). *Stikstof en fosfaat per melkkoe.* Retrieved from https://www.rvo.nl/sites/default/files/2019/12/Tabel-6-Stikstof-fosfaat-per-melkkoe-2019-2021.pdf

RVO. (2020). *Grofkeramische industrie MJA.* Retrieved from https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/energie-besparen/mja3-mee/stand-van-zaken/resultaten-sector-t/m2017/grofkeramische-industrie-mja

RVO. (2020). *The Netherlands list of fuels version January 2020 final.*

Šál, J., & Nováková, P. (2019). Utilization of Fermentation Residues in the Production of a Brick Block. *IOP Conference Series: Earth and Environmental Science.*

Schmidt, M. J. (2018). *Business Case Essentials.* Solution Matrix Ltd.

Sekaran, U., & Bougie, R. (2016). *Research methods for business: A skill building approach.* John Wiley & Sons.

SGC. (2012). *Basic Data on Biogas.*

Shulman, H. (2007). *Microwave assist technology for product improvement and energy efficiency.*

Silva, D. A., Cardoso, E. A., Varanda, L. D., Christoforo, A. L., & Malinovski, R. A. (2014). Economic feasibility study of three charcoal production systems using different methods. *Revista Arvore*, 185-193.

Simon, S., Naegler, T., & Gils, H. (2018). Transformation towards a renewable energy system in Brazil and Mexico-Technological and structural options for Latin America. *Energies*.

Singh, S., Gupta, D., & Jain, V. (2015). *Microwave processing of materials and applications in manufacturing industries: A review.*

Solar Magazine. (2019, April 2). *Vandersanden: 15.000 zonnepanelen door een gat het dak op.* Retrieved from https://solarmagazine.nl/nieuws-zonne-energie/i18134/vandersanden-15-000-zonnepanelen-door-een-gat-het-dak-op

Steenfabriek de Rijswaard B.V. (2019). *Steencollectie.* Retrieved from https://www.rijswaard.nl/media/2993/catalogus-ned-2019.pdf

Steenfabriek de Rijswaard B.V. (2020). *Het proces.* Retrieved from https://www.rijswaard.nl/informatie/het-proces/

Steenfabriek de Rijswaard B.V. (2020). *Team Rijswaard.* Retrieved from https://www.rijswaard.nl/over-ons/team/

Steenfabriek Klinkers B.V. (2020). *Het productieproces.* Retrieved from https://www.steenfabriekklinkers.nl/het-productieproces/

Steenindustrie Strating B.V. (2020). *Over Strating.* Retrieved from http://www.strating.nl/over-strating

Steffen, B. (2020). Estimating the cost of capital for renewable energy projects. *Energy Economics*.

Stichting Historie Grofkeramiek. (2012, July). *Nieuwsbrief.* Retrieved from https://www.grofkeramiek.nl/sites/default/files/2017-07/SHG%20Nieuwsbrief%20no.%2038%20-%20juli%202012.pdf

Stichting Historie Grofkeramiek. (2020). *N.V. Rodruza Steenfabriek De Zandberg.* Retrieved from https://www.grofkeramiek.nl/grofkeramiek/show/gld-498

Stichting Historie Grofkeramiek. (2020). *Rodruza - Steenfabriek Rossum.* Retrieved from https://www.grofkeramiek.nl/grofkeramiek/show/gld-732

Stichting Historie Grofkeramiek. (2020). *Monier Dakpannenfabriek Woerden.* Retrieved from https://www.grofkeramiek.nl/grofkeramiek/show/zho-365

Stichting Historie Grofkeramiek. (2020). *Steenfabriek de Rijswaard.* Retrieved from https://www.grofkeramiek.nl/grofkeramiek/show/gld-726

Stichting Historie Grofkeramiek. (2020). *Steenfabriek Engels - Oeffelt.* Retrieved from https://www.grofkeramiek.nl/grofkeramiek/show/nbr-120
Stichting Historie Grofkeramiek. (2020). *Steenfabriek Linssen B.V.* Retrieved from https://www.grofkeramiek.nl/grofkeramiek/show/lim-960
Suh, S. (2004). Materials and energy flows in industry and ecosystem networks. *The International Journal of Life Cycle Assessment*.
Tan, R., Aviso, K., Promentilla, M., Yu, K., & Santos, J. (2019). *Introduction to Input–Output Models. In: Input-Output Models for Sustainable Industrial Systems.* Singapore: Springer.
TCKI. (2013). *Resultaten modelberekening verlengde tunneloven*. Retrieved from https://tcki.nl/resultaten-modelberekening-verlengde-tunneloven/
TCKI. (2017). *Hybridedroger eindrapport.*
TCKI. (2017). *Resultaten met Hybridedrogen*. Retrieved from https://tcki.nl/resultaten-met-hybridedrogen/
TCKI. (2018). *Validatie Rookgaswarmtewisselaar*. Retrieved from https://tcki.nl/validatie-rookgaswarmtewisselaar-2/
TCKI. (2019). *Nieuwsbrief oktober 2019*. Retrieved from https://tcki.nl/nieuwsbrief-oktober-2019/
TCKI. (2019). *TCKI Waterstof en Electrificering.* Retrieved from https://tcki.nl/wp-content/uploads/pdf/tcki-waterstof-en-elektrificering-2019.pdf
TCKI. (2020). *Verbrandingslucht en energiebesparing ovens.*
TKI. (2019). *Naar een duurzame en inclusieve industrie.* Retrieved from https://www.topsectorenergie.nl/sites/default/files/uploads/Energie%20en%20Industrie/Brochure%20projecten%20TKI%20Energie%20en%20Industrie%20NL.pdf
Treasury, H. M. S. (2014). *The green book: appraisal and evaluation in central government. 2003.* Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/685903/The_Green_Book.pdf
Van Ede, J. (2015, 05 18). *Vuurvaste ovenstenen op klantspecificatie.* Retrieved from Procesverbeteren.nl: https://www.procesverbeteren.nl/selectie_methodes/Gouda_Refractories_WorldClass.php
van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., . . . Rose, S. K. (2011). The representative concentration pathways: an overview. *Climatic Change*.
van Vuuren, D., Hoogwijk, M., Barker, T., Riahi, K., Boeters, S., Chateau, J., . . . Kram, T. (2009). Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. *Energy Policy*.
van Weezel, T. (2011, July 26). *Prijsvechten met Klei, Water en Vuur.* Retrieved from Volkskrant: https://www.volkskrant.nl/nieuws-achtergrond/prijsvechten-met-klei-water-en-vuur~b41eb359/
Vandersanden Nederland B.V. (2016, 12 20). *Vandersanden Group neemt 3 fabrieken over in Nederland en 1 in Duitsland.* Retrieved from https://www.vandersandengroup.nl/bricks/nl-nl/nieuws/vandersanden-group-neemt-3-fabrieken-over-nederland-en-1-duitsland
Vandersanden Nederland B.V. (2020). *Historiek.* Retrieved from Vandersandengroup: https://www.vandersandengroup.nl/group/nl-nl/historiek
Vandersanden Nederland B.V. (2020). *Wasserstrich gevelstenen.* Retrieved from https://www.vandersandengroup.nl/bricks/nl-nl/assortiment/gevelstenen/wasserstrich-gevelstenen
Vandersanden Nederland B.V. (n.d.). *Productieproces: van klei tot straatbaksteen.*

Vandyck, T., Keramidas, K., Kitous, A., Spadaro, J., Dingenen, R. v., Holland, M., & Saveyn, B. (2018). Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. *Nat. Commun., 9*, 1-11.

Variny, M. e. (2020). Novel Concept of Cogeneration-Integrated Heat Pump-Assisted Fractionation of Alkylation Reactor Effluent for Increased Power Production and Overall CO2 Emissions Decrease. *Processes*.

Varum, C., & Melo, C. (2010). Directions in scenario planning literature. A review of the past decades. *Futures, 42*, 355-369.

Vogt-Schilb, A., & Hallegatte, S. (2014). Marginal abatement cost curves and the optimal timing of mitigation measures. *Energy Policy, 66*, 645-653.

Vos, S. (2018). *Unieke plek! Binnenkijken bij pannenbakkerij aan de Oude Rijn.* Retrieved from Indebuurt Woerden: https://indebuurt.nl/woerden/genieten-van/binnenkijken-bij-de-pannenbakkerij~54625/

Wack, P. (1985). *Scenarios: Uncharted Waters Ahead.* Retrieved from Harvard Business Review: https://hbr-org.tudelft.idm.oclc.org/1985/09/scenarios-uncharted-waters-ahead

Weitzel, M. (2017). The role of uncertainty in future costs of key CO2 abatement technologies: a sensitivity analysis with a global computable general equilibrium model. *Mitigation and Adaptation Strategies for Global Change*, 153–173.

Wienerberger B.V. (2019). *Sociaal jaarverslag 2019.*

Wienerberger B.V. (2020). *Wat uit Bemmel komt is puur.* Retrieved from https://www.wienerberger.nl/product/gevel/producttypen/basisassortiment/series/magistrada-serie/wat-uit-bemmel-komt-is-puur.html

Wienerberger B.V. (2020). *Wienerberger History: Innovation for the Future.* Retrieved from https://www.wienerberger.com/en/about/history.html

Wilberforce, T., Baroutaji, A., Soudan, B., Al-Alami, A. H., & Olabi, A. G. (2019). Outlook of carbon capture technology and challenges. *Science of The Total Environment*, 56-72.

Williamson, O. E. (1998). Transaction costs economics: How it works, where is it headed. *De economist*, 23-58.

Wingas. (2020). *Aardgas in de hoofdrol bij baksteenproductie - In steenfabriek Huissenswaard rollen jaarlijks 75 miljoen stenen uit de oven.* Retrieved from https://www.wingas.nl/grondstof-aardgas/aardgas-voor-de-industrie/tcki/steenfabriek-huissenswaard.html

Wrisberg, N., Udo de Haes, H., Triebswetter, U., Eder, P., & Clift, R. (. (2002). *Analytical Tools for Environmental Design and Management in a Systems Perspective.* Springer.

Appendices

Appendix A

This section covers a detailed description of 36 production plants of which 35 are owned by companies represented by the KNB (see Figure 22 for their locations on a map). Seven plants (out of the 42 plants that are represented by the KNB) are not included due to lack of available information. This is probably due to their relatively small production volumes (less than 75 t per day). Although these plants are not included, the described production process and decarbonisation options in this thesis also apply to these plants.

The plants not included are:

- St. Joris Keramische Industrie BV,
- De Porceleyne Fles BV,
- Koninklijke Tichelaar Makkum,
- Steenbakkerij Zilverschoon Randwijk,
- Steenfabriek Douveren
- Steenfabriek Vogelensangh
- Wienerberger Panningen.

Furthermore, Steenfabriek de Nijverheid and Steenfabriek de Volharding are considered one entity in this thesis because both are registered at the same address (and in the EU ETS list). The name of this entity is Steenfabriek de Nijverheid. The plant not represented by the KNB but included in this thesis (and part of the EU ETS) is Gouda Refractories B.V., manufacturer of refractory products.

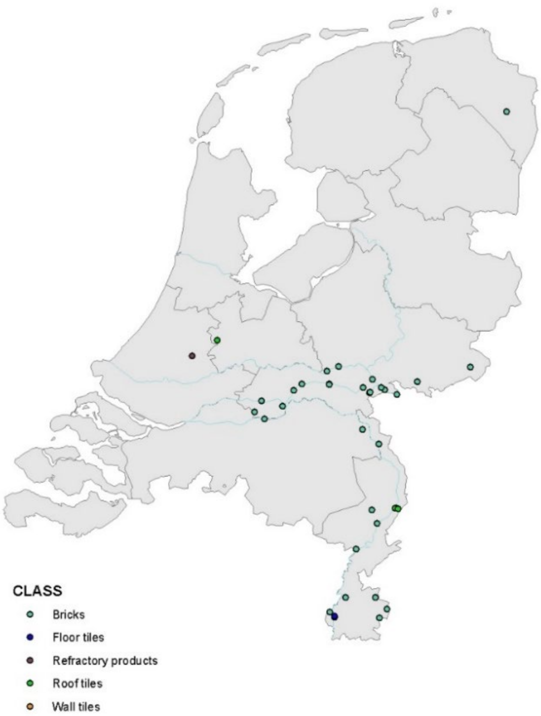


Figure 22. Map with the locations of the ceramic plants included in this thesis. Most of the plants are located next to a big river.

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 thesis: Pannenfabriek Woerden and Pannenfabriek Tegelen. Both plants are manufacturers of roof tiles. The number of employees of Monier B.V. in the Netherlands 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).

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 and Caprice Holding B.V. became the owner of Steenfabriek Huissenswaard (Caprice Holding B.V., 2020). Caprice B.V. Holding employs approximately 23 people (Bedrijvenmonitor, 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).

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. (Engels Baksteen, 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 (Engels Baksteen, 2017, pp. 8, 9). Currently, this 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 (Engels Baksteen, 2017, p. 9). The annual production capacity is 60 million bricks WF (Engels Baksteen, 2020).

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).

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).

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 a yearly 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).

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 together produce more than 6 million square meters (i.e. 30,000 to 35,000 tiles per day per plant) in more than 3000 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 100.6 million Euros in 2016 (Koninklijke Mosa B.V., 2017, p. 40).

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).

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 thesis, 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).

Steenindustrie Strating B.V.

Since 1855, bricks are manufactured at the plant currently known as Steenfabriek Strating. This plant is located in Oude Pekela and is the only remaining ceramic plant located above Arnhem in the Netherlands (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).

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 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 yearly 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 yearly 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).

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 yearly net revenues are around 200 million Euros (Wienerberger B.V., 2019; Cobouw, 2018). This thesis 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 thesis. 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 replaced their conventional light bulbs by LED-lighting and 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).

Employees and revenues

Table 20 provides an overview of all the companies and an indication of their total number of employees and yearly revenues.

Table 20 Overview of ceramic companies including their number of plants if more than one, number of employees and total net revenues.

Company	Number of employees	Total net revenues (M€)
Monier B.V. (2 plants)	180[1]	46.9
Caprice Holding B.V.	23	n.d.
Engels Baksteen (2 plants)	40	n.d.
Euro-Steenhandel B.V. (Linssen)	20	n.d.
Steenfabriek Klinkers B.V.	n.d.	n.d.
Gouda Refractories B.V.	150	50
Koninklijke Mosa B.V. (2 plants)	600	100.6
Steenfabriek de Rijswaard B.V.	45	n.d.
Rodruza B.V. (2 plants)	100	n.d.
Steenindustrie Strating B.V.	26	5
Vandersanden Nederland B.V. (5 plants)	275	70
Wienerberger B.V. (17 plants)	859	200

[1]Including two concrete roof tile plants and the head office.

Appendix B

This appendix provides an overview of all ceramic plants that are covered in this thesis. A number of plants (in total seven) is not included because no information could be derived about these plants, probably due to their relatively small size (less than 75t production per day). See Appendix A for more information.

Table 21 Overview of all production plants covered in this thesis, including their company, location, main product, calculated production, calculated production capacity and EU ETS registered CO_{2eq} emission (Nea, 2020). Both calculated production and production capacity are rounded to the nearest 5 kt.

Name plant	Owner	Location	Main product	Production (2016) kt [33]	Production capacity kt/yr	tCO_{2eq} emissions (2016)
Dakpannenfabriek Woerden	Monier B.V.	Pannenbakkerijen 1, Woerden	Roof tiles	55 to 65	70	10,359
Dakpannenfabriek 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

[33] The production value for Gouda Refractories refers to the year 2015.

Name plant	Owner	Location	Main product	Production (2016) kt [33]	Production capacity kt/yr	tCO_{2eq} emissions (2016)
Steenfabriek Strating	Steenindustrie Strating B.V.	Gelmswijk 4, Oude Pekela	Facing bricks	20 to 25	35	4,321
Kleiwarenfabriek 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
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

Name plant	Owner	Location	Main product	Production (2016) kt [33]	Production capacity kt/yr	tCO_{2eq} emissions (2016)
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

Appendix C

Bricks and roof tiles

The manufacturing processes of the bricks and roof tiles is represented by 33 plants in this thesis, 28 brick (facing, paving and inner wall bricks) manufacturers and 5 roof tile manufacturers. 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 21).

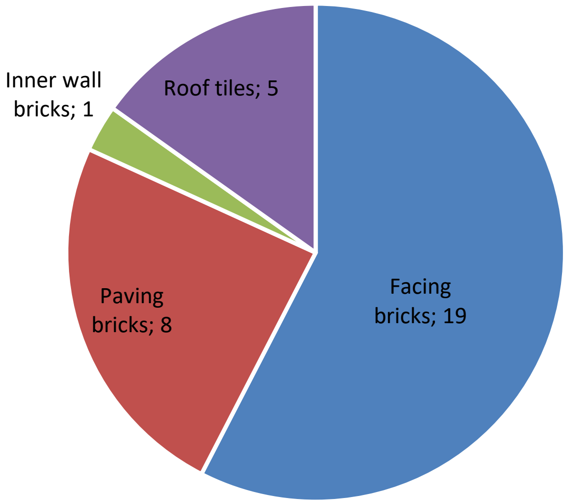


Figure 23. Number of plants producing bricks or roof tiles. The total production of these plants together approximates 2200 thousand tonnes.

Because the manufacturing processes of both bricks and roof tiles are relatively similar, they are explained here using the same process flow diagram (see Figure 24). 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 can be takes place in an intermittent or continuous way.

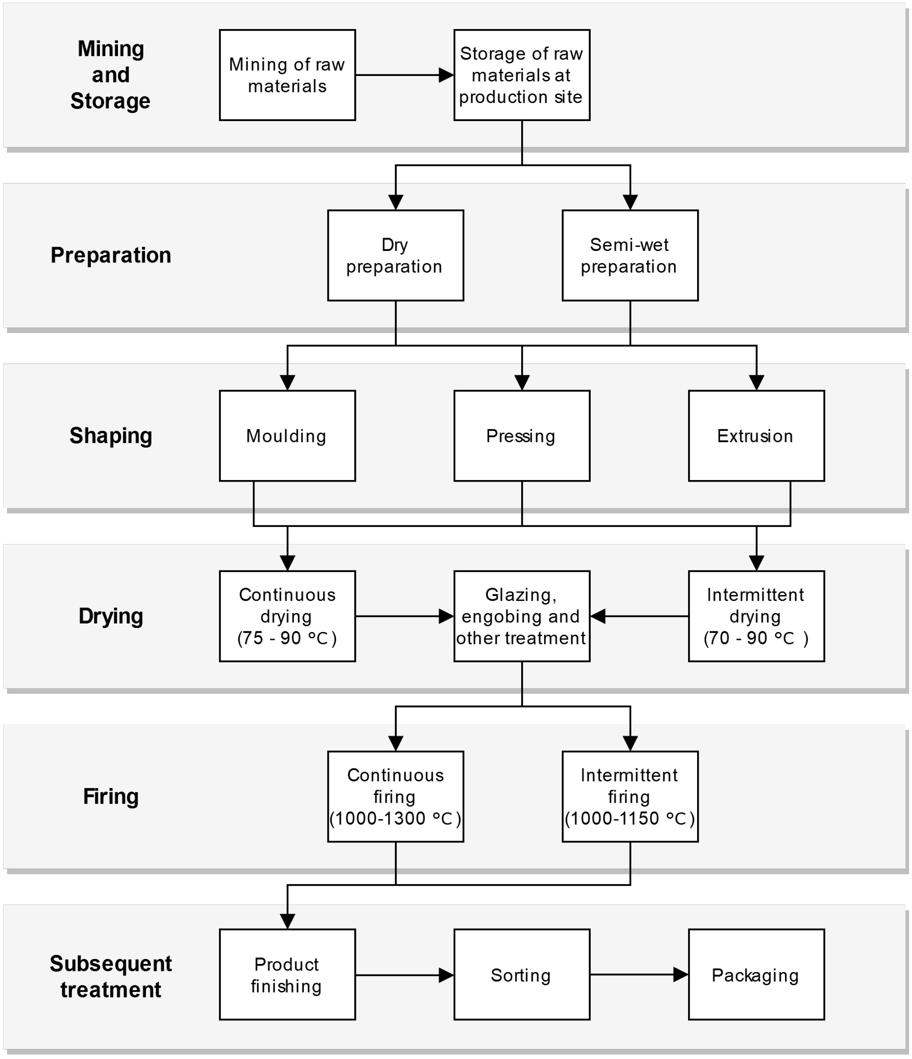


Figure 24. Production processes bricks and roof tile manufacturers.

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 25. Preparation process of a ceramic plant. Source: (KNB, 2020a).

Shaping

Three different shaping methods are used by the bricks and roof tile manufacturers in the Netherlands: moulding, pressing and extruding (see Appendix A for detailed information). 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% (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 26). Any additional required hot air is provided by natural gas burners or generated from a gas-fired combined heat and power (CHP) installation[34] and zero waste heat results from the drying process. Natural gas is for all plants the main heating source (see subsection 4.1.2).

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 bricks and roof tiles plants in the Netherlands are assumed to make use of continuous tunnel kilns. As shown by Figure 26, 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

[34] 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).

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).

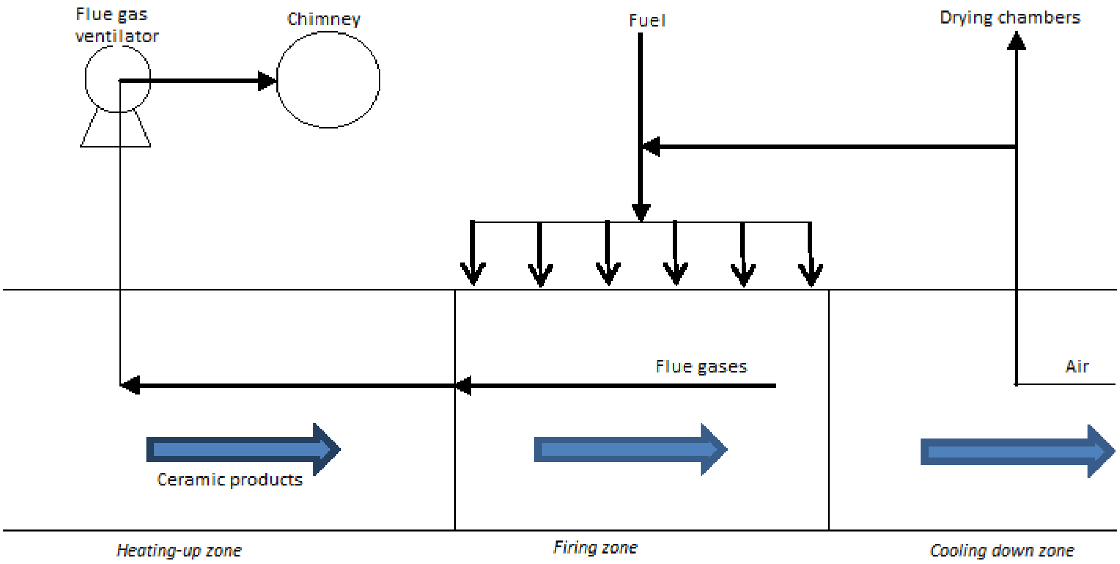


Figure 26. Three phases of the firing process in a tunnel kiln: heating-up, firing and cooling down zone. Source: captured and translated from (Ecosys, 2014, p. 36).

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 (Steenfabriek de Rijswaard B.V., 2019, p. 94).

After any product finishing techniques, the bricks or roof tiles are sorted and packaged (see Figure 27) to be stored at the stockyard, which can be covered by a roof to prevent moisture and algae damaging the finished products.

Figure 27. Packaging machine of bricks (KNB, 2020a).

Wall and floor tiles
There are two manufacturing locations of wall and floor tiles in the Netherlands, both owned and operated by the company Mosa. Wall and floor tiles have a different manufacturing process 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, feldspar, 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 (Koninklijke Mosa B.V., 2017, p. 54).

Figure 28 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.

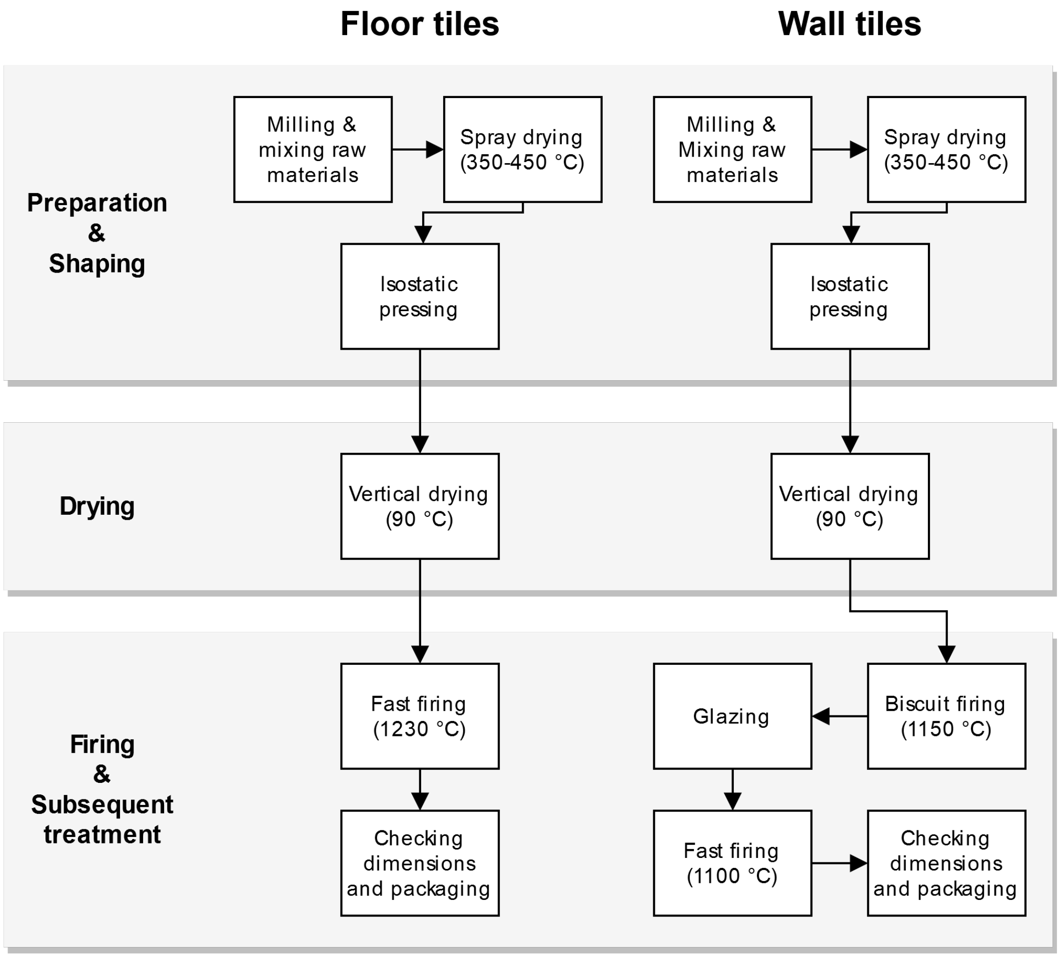


Figure 28. Production process steps of wall and floor tiles. Source: Adapted from (Koninklijke Mosa B.V.).

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. To decrease the particle size of the substances even more, 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 (Koninklijke Mosa B.V., 2017, p. 54).

Drying

After shaping the tiles, drying is applied to further decrease the water content. This process is done using vertical drying in a 'drying tower' 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% (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 28, wall tiles have an extra process step: biscuit firing[35] and glazing. According to Mosa, this is necessary for optimal colouring and shining properties (Koninklijke Mosa B.V., 2017, p. 29). 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 (Koninklijke Mosa B.V., 2017, p. 54; EC, 2007, p. 63).

Figure 29. The outside of fast firing roller kilns (KNB, 2020a).

Refractory products

Refractory, prefab and concrete products are produced at one plant in the Netherlands: Gouda Refractories. The emphasis of this thesis is on refractory bricks, for which the production processes and flow diagram are explained below.

Production process

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).

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

Appendix D

This section discussed the tables and figures that provide input for the ranges in Figure 20.

Table 22 Price and discount ranges that are used for the sensitivity analysis.

Energy source	-80%	-60%	-40%	-20%	0%	+20%	+40%	+60%	+80%	+100%
Electricity (€/GJ)	2.9	5.9	8.8	11.8	14.7	17.7	20.6	23.6	26.5	29.4
Natural gas (€/GJ)	1.5	3	4.5	6	7.5	9	10.5	12	13.5	15
Hydrogen (€/GJ)	6	12	18	24	30	x	x	x	x	x
Social rate	0.8%	1.6%	2.4%	3.2%	4.0%	4.8%	5.6%	6.4%	7.2%	8.0%

Electricity price

Figure 30 shows the marginal abatement costs of the decarbonisation options for different electricity prices. The base price (at 0% change) is 14.72 €/GJ. Changing this electricity price affects four out of seven options, with electric heating being the most sensitive. Electric heating becomes the second most cost-effective option when an electricity price is taken of 6 €/GJ (-60% change). The slightest effect of changing the electricity price is on the CCS, which MAC is only changed a little by different electricity prices. Furthermore, the MAC of industrial heat pumps becomes negative at an electricity price of 10 €/GJ (-30% change). From this point, it becomes economically attractive to invest in industrial heat pumps instead of gas fired burners for the drying process. Lastly, it is interesting to note that for extremely high electricity prices (more than +100% change), green gas by onsite digestion becomes economically the most attractive.

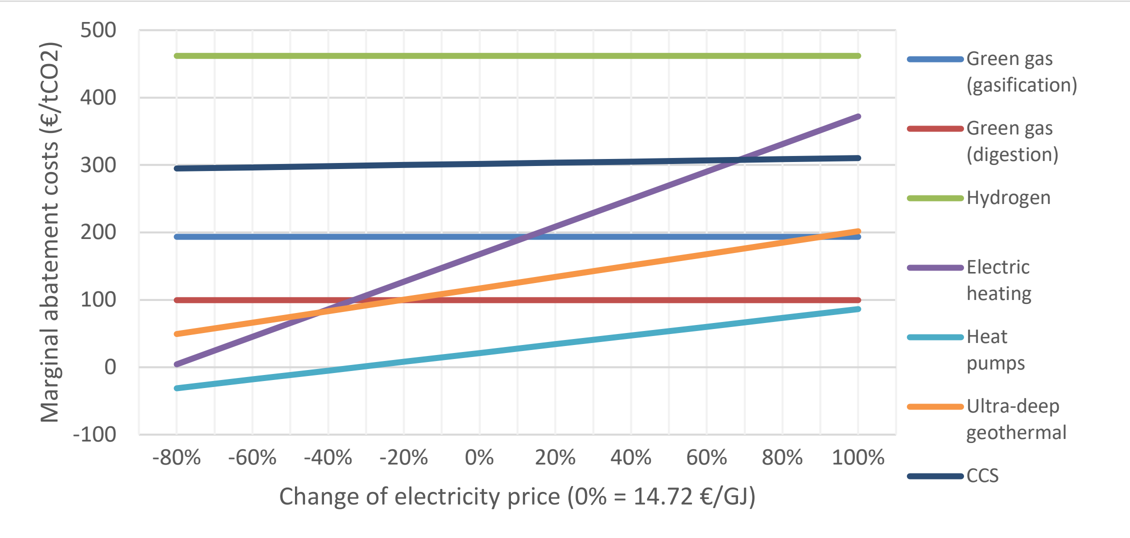


Figure 30. Sensitivity analysis based on a different electricity price.

The MAC curves that result from the most optimistic (-80% change) and most pessimistic (+100%) change in electricity price are shown in Figure 31 and Figure 32, respectively. The MAC curves show that only for a very low electricity price the electric kiln is preferred over the green gas from digestion. However, it still results in a positive MAC for the electric kiln, which means that the reference technology is still financially more attractive. Please note that the options 'heat recovery' and 'extended tunnel kiln' are given arbitrarily values of 10 and 15 €/tCO_2, respectively.

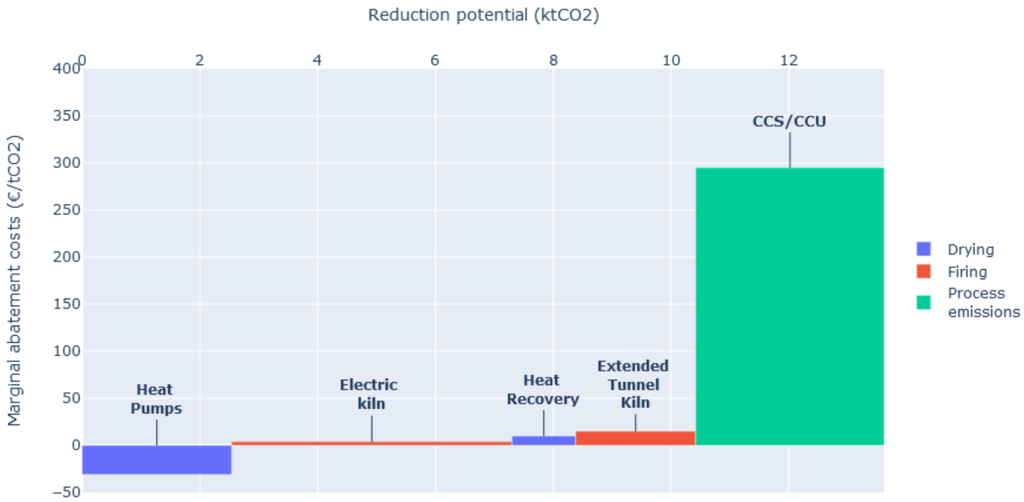


Figure 31. MAC curve of the decarbonisation options from a social perspective with a change in electricity price of -80%, resulting in 2.94 €/GJ (10.60 €/MWh).

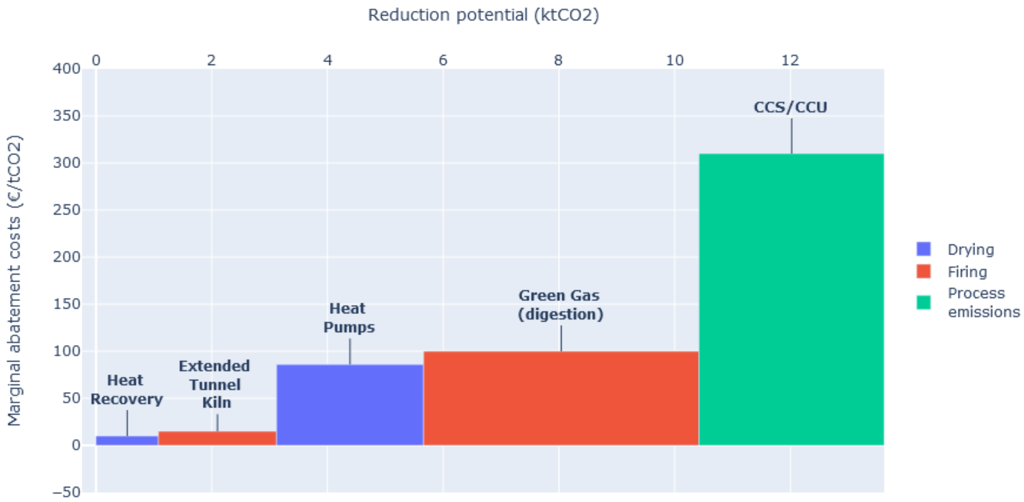


Figure 32. MAC curve of the decarbonisation options from a social perspective with a change in electricity price of +100%, resulting in 29.44 €/GJ (106 €/MWh).

Natural gas price

Besides the electricity price, it is interesting to measure the impact of a different natural gas prices on the marginal abatement cost order of the decarbonisation options. Figure 33 shows the marginal abatement costs for different natural gas prices. The base price (at 0% change) is 7.50 €/GJ. Changing this price affects all options with an opposite effect to changing the electricity price, except for CCS for which the MAC slightly increases for a higher natural gas price. The other options have a lower MAC for a higher natural gas price, all with the same sensitivity.

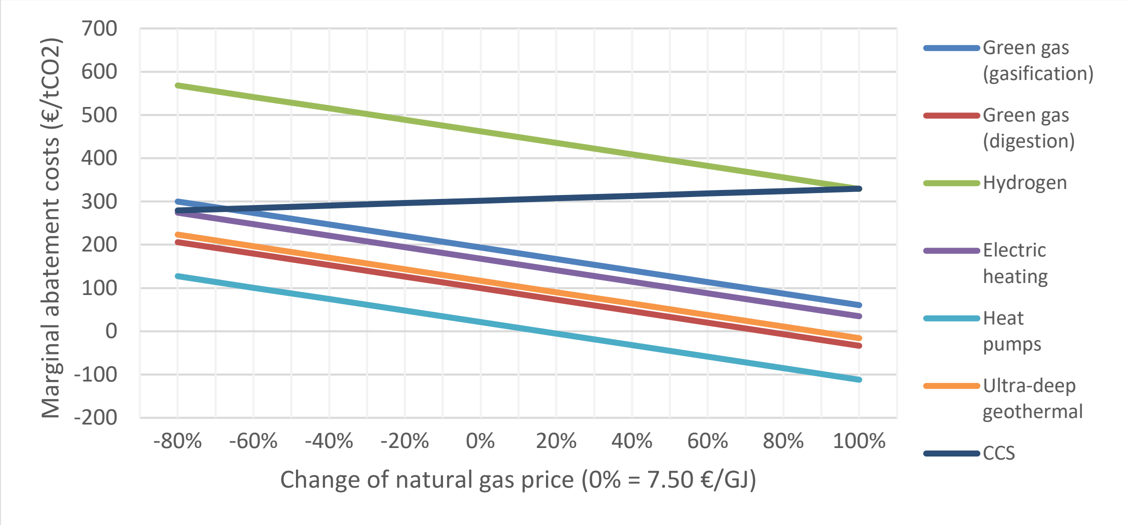


Figure 33. Sensitivity analysis based on a different natural gas price.

The MAC curves that result from the most pessimistic (+100%) change and most optimistic (-80%) change in natural gas price are shown in Figure 34 and Figure 35, respectively. The MAC curves show no differences in choice of decarbonisation options and only a decrease or an increase of the MAC. Please note that the options 'heat recovery' and 'extended tunnel kiln' are given arbitrarily values of 10 and 15 €/tCO_2, respectively.

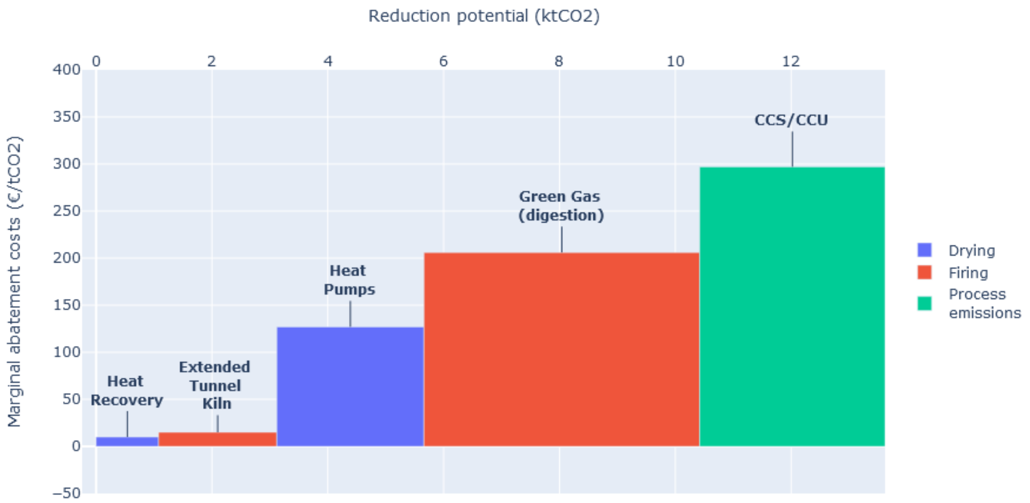


Figure 34. MAC curve of the decarbonisation options from a social perspective with a change in natural gas price of -80%, resulting in 1.50 €/GJ (5.40 €/MWh).

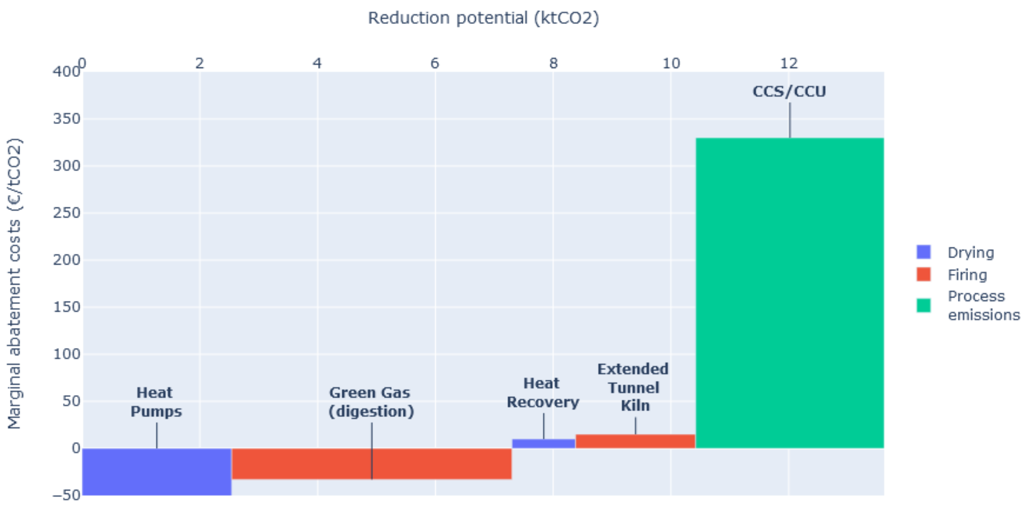


Figure 35. MAC curve of the decarbonisation options from a social perspective with a change in natural gas price of +100%, resulting in 15 €/GJ (54 €/MWh).

Hydrogen price

A different price for green hydrogen only affects the MAC of hydrogen. Because hydrogen is already the most expensive option in the base case, only results for a lower hydrogen price are analysed. It is interesting to see in Figure 36 that green hydrogen becomes the second MAC option at a price change of approximately -75%, when it is lower than green gas (digestion). The price for green hydrogen at this point is 8 €/GJ (28.8 €/MWh). The MAC of hydrogen becomes negative at -93% change (not included in the figure) which is a hydrogen price of 2 €/GJ (7.20 €/MWh).

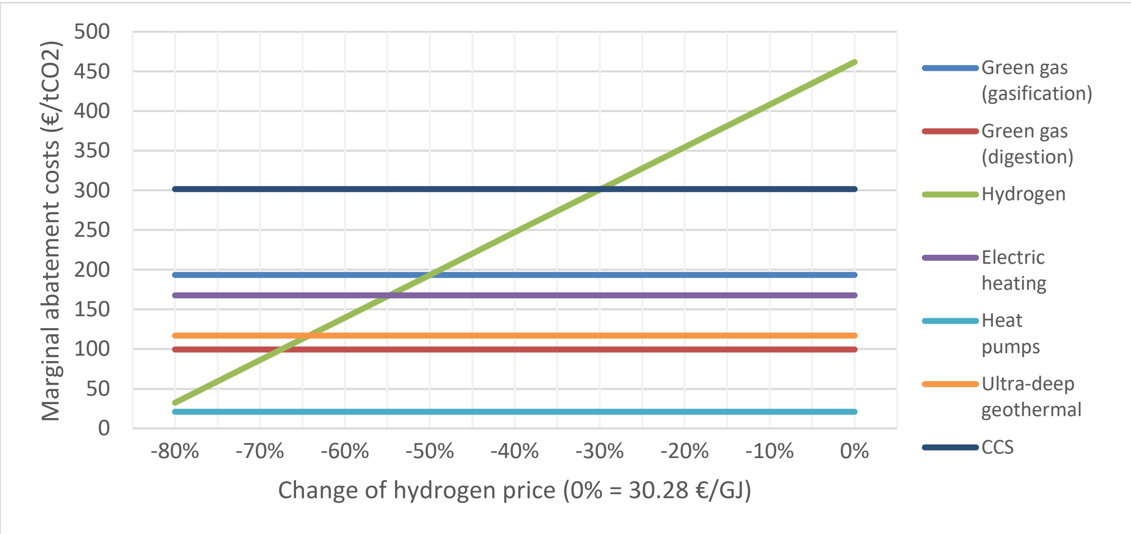


Figure 36. Sensitivity analysis based on a different hydrogen price.

The MAC curve that results from the most optimistic (-80% change) scenario is shown in Figure 37. The MAC curves shows that hydrogen has replaced green gas from digestion as decarbonisation option for the firing process. Besides that, no differences are present compared to the reference scenario due to the fact that a change in the hydrogen price only affects the hydrogen as decarbonisation option itself. Please note that the options 'heat recovery' and 'extended tunnel kiln' are given arbitrarily values of 10 and 15 €/tCO_2, respectively.

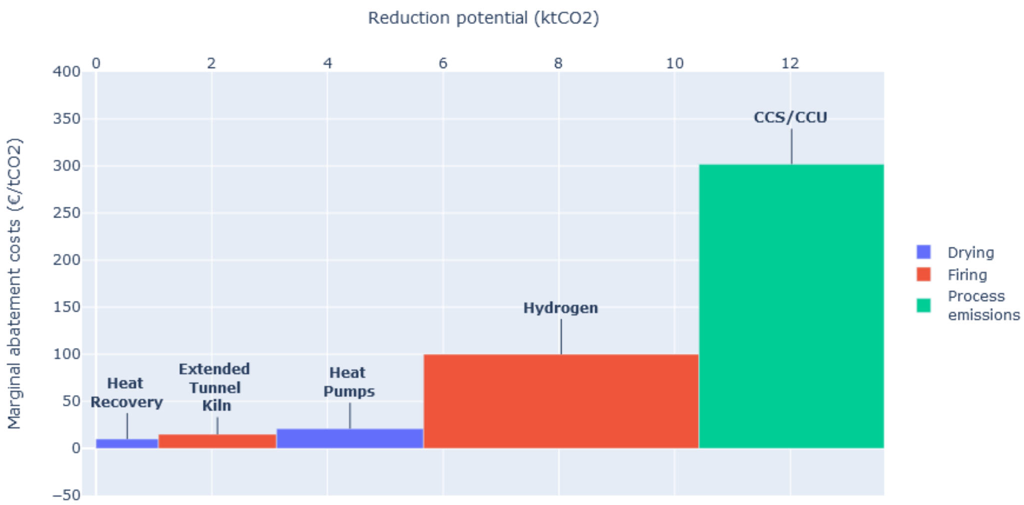


Figure 37. MAC curve of the decarbonisation options from a social perspective with a change in hydrogen price of -80%, resulting in 6.06 €/GJ (22 €/MWh).

Private discount rate

Figure 38 shows the MAC of the decarbonisation options for different values of the discount rate. The most optimistic scenario is -80% and the most pessimistic scenario is +100%, which result in a discount rate of 1.8% and 18%, respectively. No MAC curves are constructed because it becomes clear from Figure 38 that the same decarbonisation options will be present in the MAC curve, and heat pumps is the only option that becomes negative when the discount rate is lower than 9.6%.

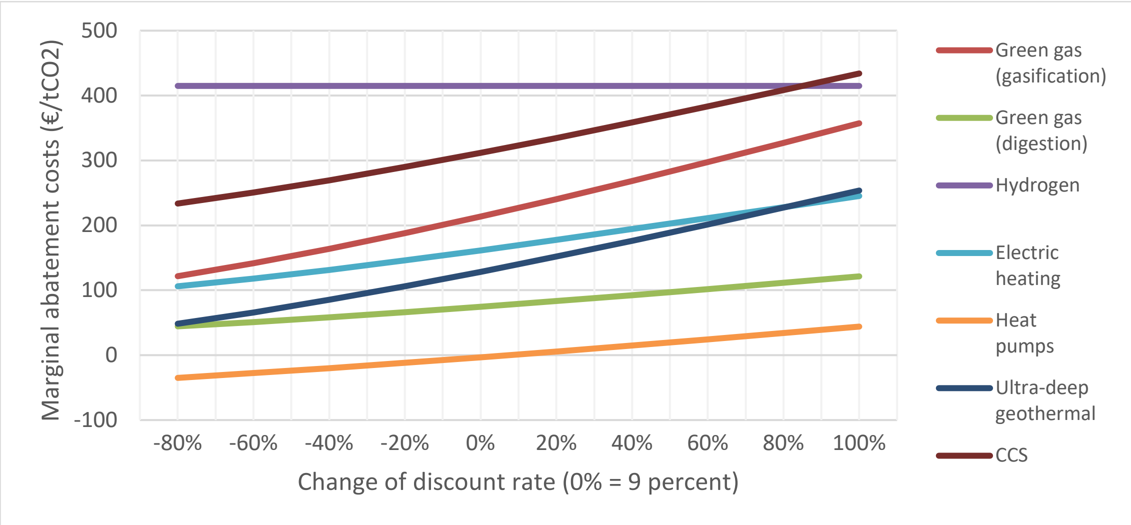


Figure 38. Sensitivity analysis based on a different social discount rate.

Appendix E

This section describes the calculation method for determining the energy savings of the four decarbonisation options: heat recovery, industrial heat pumps, hybrid drying and extended tunnel kiln. For each of the products

Heat recovery

For the heat recovery, it is assumed that the upper limit is reached of the given heat capture range (400-625 kW, see subsection 4.3.5). This is translated to GJ/t by multiplying 625 kW with 80,000 hours operation per year, dividing by the total production (10,000 t) and multiplying by 0.0036 to change kWh/t into GJ/t. The result is 0.225 GJ/t. All calculations below are depending on the energy required for the drying process that replaces the reference technology (gas-fired drying). The energy improvement is divided by the energy required for the whole manufacturing process.

- ➔ Bricks and roof tiles: 0.225 GJ/t divided by 2.55 GJ/t = **9%**
- ➔ Floor tiles: 0.225 GJ/t divided by 7.55 GJ/t = **3%**
- ➔ Wall tiles: 0.225 GJ/t divided by 10.22 GJ/t = **2%**
- ➔ Refractory products: 0.225 GJ/t divided by 5.83 GJ/t = **4%**

Industrial heat pumps

Only 25% of the energy is required compared to the reference technology, resulting in an energy efficiency improvement of 75%. Therefore, each product's energy requirements for the drying process is multiplied by (1 – 25%) and divided by the total energy consumption to calculate the efficiency improvement.

- ➔ Bricks and roof tiles: 0.81 GJ/t * 0.75 divided by 2.55 GJ/t = **24%**
- ➔ Floor tiles: 0.47 GJ/t * 0.75 divided by 7.55 GJ/t = **5%**
- ➔ Wall tiles: 0.74 GJ/t * 0.75 divided by 10.22 GJ/t = **5%**
- ➔ Refractory products: 0.48 GJ/t * 0.75 divided by 5.83 GJ/t = **11%**

Hybrid drying

The same calculation is used as for industrial heat pumps, using 1-75% instead of 1 – 25%.

- ➔ Bricks and roof tiles: 0.81 GJ/t * 0.25 divided by 2.55 GJ/t = **8%**
- ➔ Floor tiles: 0.47 GJ/t * 0.25 divided by 7.55 GJ/t = **2%**
- ➔ Wall tiles: 0.74 GJ/t * 0.25 divided by 10.22 GJ/t = **2%**
- ➔ Refractory products: 0.48 GJ/t * 0.25 divided by 5.83 GJ/t = **3%**

Extended tunnel kiln

The extended tunnel kiln technology is the only technology that directly improves the energy efficiency of the firing process by 30%. For the whole production process, this results in an efficiency improvement of 18% and 19% for bricks and roof tiles, and refractory products, respectively. This technology is not applicable to wall and floor tiles because no tunnel kiln is used in their manufacturing process.

- ➔ Bricks and Roof tiles: an efficiency improvement of 30% for the firing process results in 0.3 * 1.5 GJ/t = 0.45 GJ/t less energy needed. This results for the whole manufacturing process in 0.45 GJ/t / 2.54 GJ/t = **18%**
- ➔ Refractory products: using the same method as for bricks and roof tiles gives the following equation and result: 0.3 * 3.57 GJ/t / 5.56 GJ/t = **19%**

Appendix F

This section shows the Python code to construct MAC curves in this thesis, the example code below is for the MAC curves from a social discount rate (4%). The code is run in a surface of Google Colab: https://colab.research.google.com.

```
import numpy as np
import pandas as pd
import plotly.graph_objects as go
import plotly.express as px
from plotly.subplots import make_subplots

#SMAC1
fig = go.Figure()

hoogtes = [10,15,21,100,302]
breedtes = [1.08,2.04,2.54,4.76,3.2]
text = '<b>Heat <br>Recovery,<b>Extended <br>Tunnel <br>Kiln,<b>Heat <br> Pumps,<b>Green
 Gas <br>(digestion),<b>CCS/CCU'.split(',')

categorieen = [0,1,0,1,2]
categorie_labels = ['Drying', 'Firing', 'Process <br>emissions']
categorie_kleuren = px.colors.qualitative.Plotly

middenpunten = np.cumsum(breedtes) -  np.array(breedtes) / 2

fig.add_trace(go.Bar(
    x=middenpunten, y=hoogtes, width=breedtes,
    # text=text, textposition="auto",
    xaxis='x2', showlegend=False,
    marker_color=[categorie_kleuren[i] for i in categorieen]
))

# Voeg leeg plaatje toe om tweede x-as te maken en categorie-labels toe te voegen
for i in np.unique(categorieen):
    fig.add_trace(go.Bar(x=[None], y=[None], xaxis='x2', marker_color=categorie_kleuren[
i], name=categorie_labels[i]))

for i in range(0,len(text),1):
 fig.add_annotation(go.layout.Annotation(
     x=middenpunten[i], y=max(0,hoogtes[i]), ax=(-50 if hoogtes[i] > 2000 else 0), ay=(-
30 if hoogtes[i] > 2000 else -
40), text=text[i], textangle=(0 if hoogtes[i] > 2000 else 0)
))


for i in range (1,len(text),2):
 fig.add_trace(go.Scatter(
 x=[middenpunten[i],middenpunten[i]],y=[min(0,hoogtes[i]),0],
```

```
 mode='lines',line_color='#2A3F5F',
 line_width=1, showlegend=False
))

fig.update_layout(
    width=900,
    height=450,
    margin={'t': 70, 'b': 20},
   xaxis2 = {
        'tickvals': middenpunten,
        'ticktext': [t if i % 2 == 2 else '' for i,t in enumerate(text)],
   },
    xaxis = {'title': 'Reduction potential (ktCO2)', 'matches': 'x2', 'overlaying': 'x2'
, 'side': 'top'},
    yaxis_title='Marginal abatement costs (€/tCO2)',
    legend_y=0.5,
   # xaxis_range=[0,1500],
    yaxis_range=[-50,400],

)
```