# Decarbonisation options for the ceramic industry in the Netherlands

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## Abstract

The manufacturing processes of the Dutch ceramic plants are energy intensive with high temperatures. Most heat is generated by firing natural gas, which causes $CO_2$ emissions. According to the Dutch Climate Agreement, the ceramic plants need to abate their $CO_2$ emissions by 2030. This study intends to provide an analysis of applicable decarbonisation options from a techno-economic perspective. The most cost-beneficial decarbonisation options are analysed by marginal abatement cost curves and evaluated by a business case analysis. The results show that in 2030 a combination of industrial heat pumps, green gas from onsite digestion and CCS are most cost-beneficial and can theoretically abate the total $CO_2$ emissions by 96%. However, uncertainties are present and the supply of feedstock and fuels should be considered in the decision-making process. Next steps for research could be a applying socio-technical approach or a detailed case study of one or more plants.

Keywords: techno-economic perspective, carbon emissions, ceramic industry, bricks and roof tiles, decarbonisation technologies, marginal abatement costs, business case analysis.

## 1. Introduction

The Dutch climate agreement ('Klimaatakkoord'), which was introduced in 2019, has set a target for 2030 for the Dutch industrial sector to abate its $CO_2$eq emissions by 19.4 Mt compared to 2015 (Klimaatakkoord, 2019). The long-term goal is to reduce the total $CO_2$eq 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 $CO_2$eq emission profile of approximately 500 thousand tonnes. 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 less than 0.6%. Because the ceramic industry is part of the industrial sector, 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 as soon as possible (Gasterra, 2019). 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.

Only brief explanations are given about the manufacturing processes of the ceramic industry in public sources by the ceramic companies and related research institutes like the Technical Centre for the Ceramic Industry (TCKI). The source that provides most detailed information about the ceramic manufacturing processes comes from the European Commission: The Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry (BREF) (EC, 2007). Nevertheless, numbers are not complete in this BREF, especially regarding greenhouse gas emissions. And mainly due to the fact that the BREF covers the whole ceramic industry in Europe, it is difficult for parties to determine what alternatives and related factors are applicable to them (Ibáñez-Forés, Bovea, & Azapagic, 2013). 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.

Besides the detailed knowledge of the ceramic manufacturing processes, only a small number of academic papers are written about the decarbonisation (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 finally, Ibn-Mohammed, et al. (2019) concentrates only on the decarbonisation options for a specific process step (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.

Lastly, the shift from the current ceramic production process to a more sustainable production process with less $CO_2$ emissions is not immediately possible, due to the lifetime of currently used technologies and decarbonisation options that cannot directly be implemented. Therefore, decarbonisation pathways are required to enable an analysis of implementation of decarbonisation options. Future scenarios can be constructed to determine these factors 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).

This research intents to fill the knowledge gaps discussed in the former section and therewith provides a clear and detailed overview of the ceramic production process, including an analysis of different decarbonisation pathways starting in the year 2030. This specific starting 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 research is to provide guidance to implementing the right decarbonisation option. In other words, it is determined whether a business case is available to decarbonise their production process.

From the stated knowledge gaps and described research objective, it can be concluded that the decarbonisation of the different ceramic manufacturing processes plays a central role in this paper and 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. In the methodology, the techno-economic perspective is further discussed. 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?"***

The scope of this research includes all ceramic plants in the Netherlands that are member of the KNB, and Gouda Refractories, which is not represented by the KNB[1]. Considering the process characteristics, only the processes are analysed that take place within the walls of the ceramic plants. This means that, for example, determining the CO2 emissions that result from transporting finished products to a warehouse is not in the scope of this research. Considering the decarbonisation options, their whole system is included in this research. For instance, the availability of required feedstock and the deposition of possible rest material is within the scope of this research. Finally, there is no limit to time, though the focus is on the year 2030.

The remainder of this paper is structured as follows. Section 2 discusses the methodology of this study which includes the application of a techno-economic perspective, including the system analysis, marginal abatement cost (MAC) curves and a business case analysis (BCA). Section 3 provides a system analysis of the ceramic production processes in the Netherlands and section 4 discusses the decarbonisation options. Section 5 states the results and section 6 the discussion. Finally, section 7 concludes on this paper.

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

## 2. Methodology

### *2.1 Techno-economic perspective*

The use of different perspectives is 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. The techno-economic perspective has IAMS and long-term clime-energy scenarios as its examples of models and applications. This techno-economic perspective uses a supply-demand balance of the energy flows which can be seen as in conjunction with the neoclassical economic approach. The techno-economic perspective can be applied through IAMs to estimate the costs of climate stabilisation policies (Clarke & Jiang, 2014). However, Edelenbosch, et al. (2017) argues that IAMs do not have 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 also made by Weitzel (2017) who stresses that regional assessment of mitigation technologies are needed because global averages can hide important consequences.

The starting point of applying the techno-economic perspective in this research is determining the reference levels, such as starting year and technology and/or efficiency changes. The research of this research has a reference year 2030 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). Several other studies that assessed $CO_2$ reduction options in industry have followed a frozen-technology reference level (e.g. Kuramochi (2016), Variny (2020)).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, a bottom-up approach is considered best applicable, since the analysis concentrates on the level of energy systems and saving options. 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.

### *2.2 System analysis*

The first step of applying the techno-economic perspective is creating an overview of the ceramic industry in the Netherlands and relevant decarbonisation options. The system analysis will be conducted by thorough desk research and consultation with plants 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).

The mass and energy flows are partially derived from literature from publicly available sources, scientific literature and 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:

$$\sum\varphi_{x,in} = \sum\varphi_{x,out} \qquad (2.1)$$

Where $\varphi_{x,in}$ [t] is the mass of the 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 (equation 2.2) and second, equation 1.3 that describes the energy flow.

$$Q_{in} = Q_{out} + Q_{losses} \qquad (2.2)$$

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.

$$Q_j = \varphi_j * cp_j * (T_j - T_0) \qquad (2.3)$$

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

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. 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.

### *2.3 MAC analysis*

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 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. 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 & Envist (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 (i.e. production costs). An example of such transaction costs are implementation costs (e.g. training programs. Next to the transaction costs, institutional costs and non-monetary costs are excluded (Vogt-Schilb & Hallegatte, 2014). The second critical note of Nauclér & Envist (2009) is that behavioural changes are not included in the MAC. Behavioural changes can be driven by price and non-price factors. Examples of such factors are awareness campaigns or policy changes. In addition to the critical notes stated by the authors themselves, Kesicki & Ekins (2012) have published a paper in which they discuss the McKinsey & Company report. The first important 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).

An important aspect of assessing MACs is the discount rate (Kesicki & Strachan, 2011). Discount rates are used to compare costs in different time periods. 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 the time preference, which results in a social discount rate that generally 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 decarbonisation options are used to construct a MAC curve from a social and private perspective. The difference in calculations 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 mostly 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% (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 has 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 considering the varying cost of capital for different parts of the world or only concentrating on one or similar countries (Ondraczek, Komendantova, & Patt, 2015). Since 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 correct, a sensitivity analysis will be conducted to measure the impact of the discount rate.

Considering the other input parameters, the systemic focus should be on energy flows and markets when a techno-economic approach is used (Cherp, et al., 2018). Therefore, techno-economic parameters are required. Such techno-economic parameters have been applied in literature that conducted similar research. For example, Horvath, et al. (2018) and Chiuta, et al. (2016) state 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).

For each of the decarbonisation options, a similar calculation method is applied to determine the MACs and other parameters relevant for the BCA. An important part of this calculation is covered by comparing the decarbonisation option with the reference technology. The reference technology is the technology that is (partly) replaced by the decarbonisation option. The MAC is determined 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, the fuel prices and $CO_2$ tax are explained in detail.

***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 study, 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[2]) 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 is used in this study, 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 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 study 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 €/t$CO_2$, derived from the KEV 2019 (PBL, et al., 2019). If a Dutch $CO_2$ tax also is present in 2030, it is assumed

[2] Low Heated Value, also known as Low Calorific Value. Energy content is 0.03165 GJ/$m^3$ (RVO, 2020).

that this Dutch $CO_2$ tax is below the European $CO_2$ tax, i.e. below 47 €/t$CO_2$. The $CO_2$ tax is only included in the MAC calculations from a private perspective.

To calculate the marginal abatement costs, the following equations 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 by Kesicki & Ekins (2012). The first equation calculates the marginal abatement cost:

$$C_{spec,CO_2} = \frac{\alpha \cdot I + C - B}{\Delta M_{CO_2}} \quad (2.4)$$

Where:
$\alpha \cdot I$ = annual capital costs
C = annual operation and maintenance costs
B = annual benefits
$\Delta M_{CO2}$ = annual amount of avoided $CO_2$ emissions

The capital recovery factor α in equation 2.5 is determined by the following calculation:

$$\alpha = \frac{r}{1-(1+r)^{-n}} \quad (2.5)$$

Where:
α = capital recovery factor
r = discount rate
n = life time or depreciation period of equipment

### *2.5 BCA*

The BCA has been widely used for many purposes and applications, for example for 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, such as $CO_2$ 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).

In this thesis, 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 below. Literature shows that the three evaluation techniques are applied in techno-economic analysis of renewable technologies, such as biomass gasification (Cardoso, Silva, & Eusébio, 2019).

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:

$$NPV = -I + \frac{B-C}{\alpha} \quad (2.6)$$

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. Furthermore, the $CO_2$ cost is included in the annual costs of the reference option 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.

Since the NPV is an absolute figure, it might give an insufficient indication of a business case. Therefore, another parameter is included in this study. This parameter is the pay-back-period (PBP), which shows in how many years the investment costs are returned. This study 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:

$$PBP = \frac{I}{B-C} \qquad (2.7)$$

Where $I$ [€] is the initial investment, and $B - C$ [€/yr] is the annual difference in costs between the reference option and the decarbonisation option. The PBP is considered a rule of thumb since it is relatively easy to determine, but it ignores any changes in annual costs or benefits. Moreover, it does not include the discount rate. Considering these shortcomings of the PBP, a third parameter is determined to analyse the decarbonisation technologies: the internal rate of return.

The third parameter is the internal rate of return (IRR). This rate gives a better indication than PBP 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 per cent is desired, which is usually higher than interest rates applied by banks (Blok & Nieuwlaar, 2017). However, it is unsure whether this rate of 10 per cent 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. System analysis

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

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

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 1*** 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.

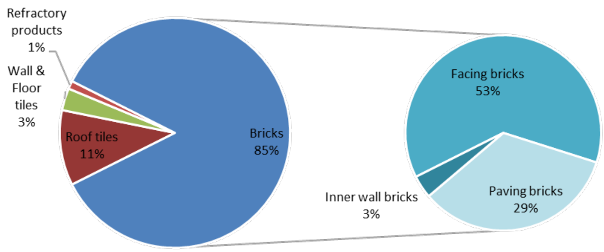


***Figure 1. Production share of tonnes ceramic products manufactured.***

The manufacturing process of ceramic products is subdivided in six general process steps: 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 process step, 'mining and storage', is not included in this research in terms of energy consumption. A detailed description of the processes per product category can be found in the Appendix.

### *3.1 Bricks and roof tiles*

***Figure 2*** 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). The figure shows that five process blocks are simplified into two process blocks. The first block has only fuel emissions (0.046 $tCO_2$ per tonne end product), which results from additional heating with natural gas during the drying process. The preparation and shaping process only have electricity as energy input. The second block shows fuel emissions (0.085 $tCO_2$ per tonne end product) and process emissions (0.047 $tCO_2$ per tonne end product). These emissions are the result of heating the bricks by natural gas during the firing process. These results show that the drying and firing process are the two critical processes of the bricks and roof tiles production process.

BRICKS AND ROOFTILES

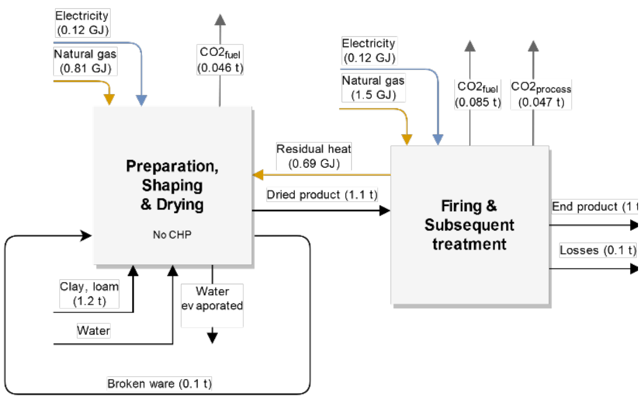


*Figure 2. Flow diagram of the manufacturing process of bricks and roof tiles, including mass, energy and CO2 emissions flows.*

### 3.1 Floor and wall tiles

*Figure 3* and *Figure 4* show the material, energy and $CO_2$ emissions flow diagram of floor and wall tiles, respectively. The total energy consumption is 7.63 GJ per tonne end product and 10.22 GJ per tonne end product 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 2*), the figures show three process blocks instead of two to describe the process flows. The additional block is created to distinguish the spray drying (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.

FLOOR TILES

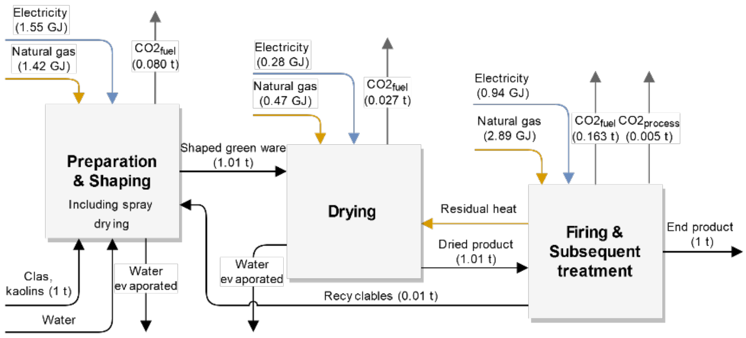


*Figure 3. Flow diagram of the manufacturing process of floor tiles, including mass, energy and CO2 emissions flows.*

WALL TILES

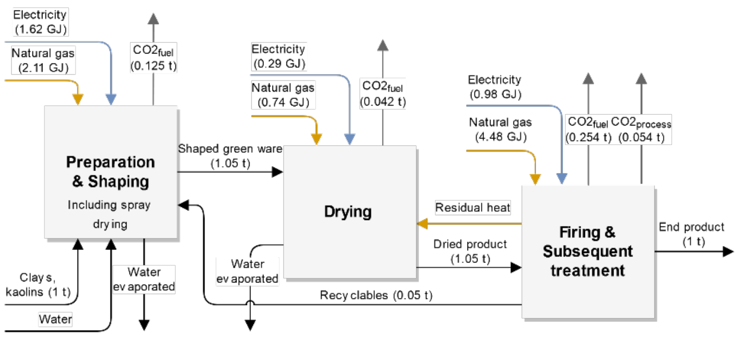


*Figure 4. Flow diagram of the manufacturing process of wall tiles, including mass, energy and CO2 emissions flows.*

### 3.3 Refractory products

*Figure 5* shows the material, energy and $CO_2$ emissions flow diagram of refractory products.

REFRACTORY PRODUCTS

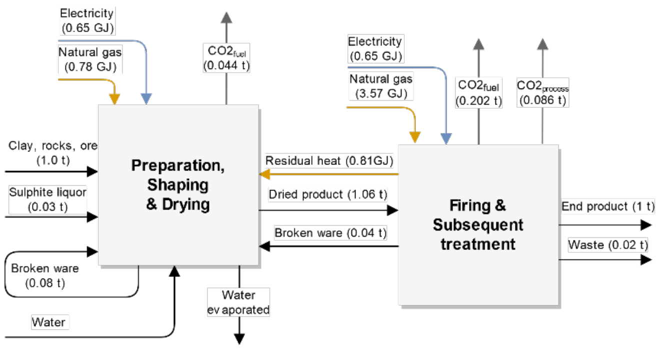


*Figure 5. Mass, energy and CO2 emissions flow diagram of refractory products.*

## 4. Decarbonisation technologies

The mass, energy and $CO_2$ emissions flow diagrams show that drying and firing are the two most critical processes considering $CO_2$ emissions. Both processes require the same amount of energy, but drying requires less (additional) firing from natural gas due to the supply of waste heat from the firing process. Since bricks and roof tiles together have a production share of more than 95 per cent in the Netherlands, their drying and firing process steps are used to determine options for decarbonisation and further calculations with those decarbonisation options. It is therefore assumed that the decarbonisation options discussed 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 provided, the reference technology is described. This reference technology is partly or fully replaced by the decarbonisation option and is required to perform the calculations for the MACs 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 1* states the different parameters of this reference unit that are used in the calculation method.

*Table 1 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** | kt$CO_2$/yr | 6.77 |
| **SEC drying** | GJ/t | 0.8 |
| **Specific $CO_2$ emissions drying** | kt$CO_2$/yr | 3.61 |

The decarbonisation technologies are identified through desk research of publicly available sources. Two 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. As a result, the decarbonisation options could not been validated or discussed in detail with the ceramic industry. Nevertheless, the overview of decarbonisation options is generally discussed with different ceramic companies (e.g. Braas Monier, Vandersanden, and Wienerberger) during a meeting that was initiated by the KNB.

The categories that are covered by the decarbonisation options are:

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

*Table 2* provides an overview of the different decarbonisation options that are applicable to the ceramic industry in the Netherlands. The techno-economic parameters in *Table 2* 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% of production in tonnes of the total ceramic industry in the Netherlands. The 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%) are 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. In the appendix, all technologies are further discussed.

*Table 2 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 exchange** | 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 |

## 5. Results

### *5.1 MAC from a social perspective*

*Table 3* shows the results of the MACs for the decarbonisation options. 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 GJ/t for the drying process and 6.8 GJ/t 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 per cent.

*Table 3 Marginal abatement costs of the decarbonisation options form a social perspective.*

| Decarbonisation option | Relevant process(es) | Maximum reduction ($ktCO_2$) | 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 | 302 |

### Efficiency improvement

For some decarbonisation options no parameters could be derived to calculate the 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 different types of ceramic products: bricks & roof tiles, floor & 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 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 4*). 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.

*Table 4 Efficiency improvement parameters. These values are applicable to the manufacturing process of bricks and roof tiles.*

| 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% |

Industrial heat pumps have the highest efficiency improvement, which is a result of using only 25% of the input energy compared to the reference option (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.

### *5.1 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 and the SEC per process step. ***Figure 6*** 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. 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 per cent 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 6*** 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 per cent 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.

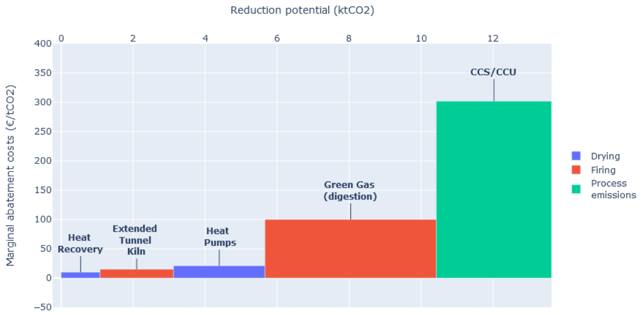


***Figure 6. MAC curve of the decarbonisation options from a social perspective with a discount rate of 4% in 2030.***

**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 per cent. However, this resulted in barely any differences the order of the MAC curve of the decarbonisation options. Therefore, the prices have been altered to -80% as minimum and +100% as maximum. The range of values shows that the lowest prices for electricity, natural gas and hydrogen are ranging from 1.50 €/GJ to 30 €/GJ. The highest price for hydrogen is the base input price since this technology is already the most costly and increasing this price will have no influence on the order of the MAC curve or cost effectiveness of the hydrogen option.

***Table 5 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 7*** shows the from the sensitivity analysis resulting ranges of MAC for the different decarbonisation options. The maximum and minimum values of MAC of the decarbonisation technologies are derived from Figure 28, Figure 31, Figure 34 and Figure 36, which are explained in detail in Appendix C. 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 €/tCO2. 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 €/tCO2), green gas from onsite digestion (-33 €/tCO2) and ultra-deep geothermal heat (-11 €/tCO2).

## *5.2 MAC from a private perspective*

An important difference between this private perspective and the social perspective is the higher discount rate (9%) and inclusion of CO2 taxes (47 €/tCO2). The private perspective enables a better representation of the market and therefore is a better guideline for investment decisions of the ceramic plants than using the MAC from a social perspective.

Because two added parameters (i.e. higher discount rate and inclusion of CO2 taxes) influence the MAC from a private perspective, the calculation of the MAC is given in three steps (see Table 15). First the MAC from a social perspective is given, then effect of a higher discount rate, and third the inclusion of CO2 taxes. Altogether, this adds up to the MAC from a private perspective.

***Table 6 MAC of the decarbonisation options from a private perspective. The effect of a private discount rate, the effect of a CO2 tax, and the MAC from a private perspective are given. All numbers are given in €/tCO2.***

| 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 6*** 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 €/t$CO_2$) and no effect on hydrogen (due to zero investment costs). The average increase in MAC caused by the change in discount rate is 38 €/t$CO_2$. 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 the decarbonisation option.

## *5.3 Mac curve from a private perspective*

The MAC curve that is constructed based on private perspective (see ***Figure 8***) shows the same order of technologies at 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 €/t$CO_2$ and -10 €/t$CO_2$ is taken, respectively. The third option - the only one that is calculated - with a negative MAC is heat pumps with a MAC of -3 €/t$CO_2$. 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.

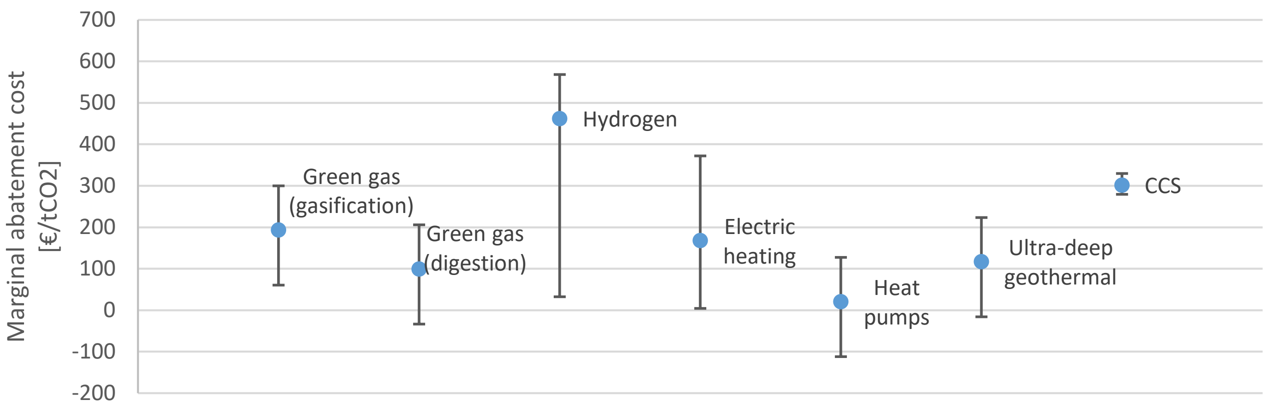


***Figure 7. Ranges of MACs of different decarbonisation options. The blue dots show the marginal abatement cost for base input.***

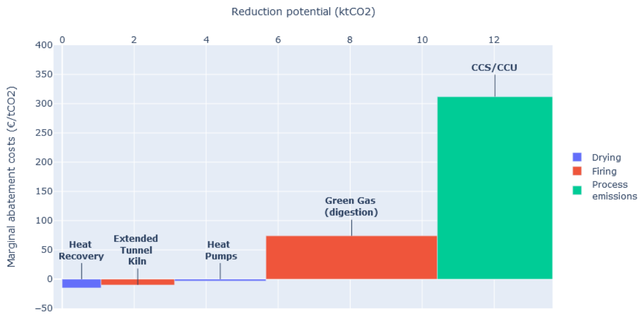


*Figure 8. MAC curve of the decarbonisation options from a private perspective.*

**Sensitivity analysis of MAC from a private perspective**

The sensitivity analysis is applied such that it is visualised what the private discount rate or $CO_2$ should be to make a decarbonisation option financially more attractive to invest in than the reference technology 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 7* shows that all options require a present $CO_2$ tax, and the height of this tax differs per options but shows large numbers. For example, six out of seven options require a $CO_2$ tax above 100 €/t$CO_2$ and four of these six options even more than 200 €/t$CO_2$. 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 7 Maximum discount rate and minimum CO2 tax required to prefer the decarbonisation option over the reference technology.*

| Decarbonisation option | Private MAC [€/t$CO_2$] | Required discount [%] | Required $CO_2$ tax [€/t$CO_2$] |
|---|---|---|---|
| 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 |

## *5.4 BCA*

To apply a BCA, the decarbonisation technologies are compared according to their NPV, PBP and IRR. *Table 8* states these parameters for the initial result, with a discount rate of 9% and $CO_2$ tax of 47 €/t$CO_2$. The table shows that only industrial heat pumps shows a positive NPV, and therefore is the only option that generates a PBP and IRR. The investment in industrial heat pumps has a positive net present value of almost 85 thousand Euro 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 8 BCA parameters.*

| Decarbonisation option | MAC (€/t$CO_2$) | 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 | 6.9 | 9.7 |
| Ultra-deep geothermal | 128 | +11 | -4,552,303 | ∞ | - |
| CCS (or utilisation) | 312 | +10 | -38,577,776 | ∞ | - |

## *5.4 Maximum PBP and minimum IRR*

The initial results of the BCA give only little information, 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 9* gives the results of what the value of the $CO_2$ tax theoretically should be to generate a maximum PBP of 5 years and a minimum IRR of 10%.

*Table 9* 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 per cent. 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 €/t$CO_2$ compared to 545 €/t$CO_2$).

***Table 9 CO2 taxes required per decarbonisation to reach a maximum PBP of 5 years and minimum IRR of 10 per cent.***

| 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 |

## 5. Discussion

**System analysis – ceramic manufacturing process**

This research has analysed the ceramic production processes from a bottom-up approach and by using an input-output analysis, this has resulted in a detailed process description 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 plant are assumed to be sufficiently available and therefore 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 the electricity network. However, due to the remote locations of the ceramic plants, a close cooperation with plants from other industries is not expected to be very 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 therefore is not further analysed in this thesis. This $CO_2$ emissions that are included by the input-output analysis is an output flow 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. As a result, this aggregation of $CO_2$ emissions has neglected specific products or production technologies. 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 use renewable firing technologies (KNB, 2020). For the current results stated by 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. Those effects on the results of this paper might be 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 there is no literature about this option, and therefore its applicability is uncertain. Furthermore, the impact on the electric grid could be considerate as the energy consumption is multiplied by a factor of 7. 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 network 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 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) should be available from nearby farms to prevent extra infrastructure problems and additional costs. 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. As long as such green gas is not possible from a nearby supplier, 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 a firing kiln, 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 option 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. This results in possible infrastructure capacity problems when applying electrification options like electric firing and drying, or (assisted) microwave firing and drying. Therefore, the timeframe and costs of increasing the electricity connection capacity has to be included in the decision-making process. 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 plan) and transport the green gas through the 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 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. 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 considering the neoclassical economics view, and therefore the limitations corresponding with this neoclassical view are not further discussed here. Another point of discussion for the BCA is the point that investments are generally irreversible and therefore testing on a large is not possible. Therefore, 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 is also considered confidential information by the 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.

## 6. Conclusion

This research 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 results of the system analysis show that total specific $CO_2$ emissions of a ceramic product ranges 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. 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 can be concluded from the research in this thesis 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 technology is the only technology that is applicable in the short term in 2030, both from a technical and economic perspective. 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***

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. 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 characteristic and the corresponding decarbonisation options.

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