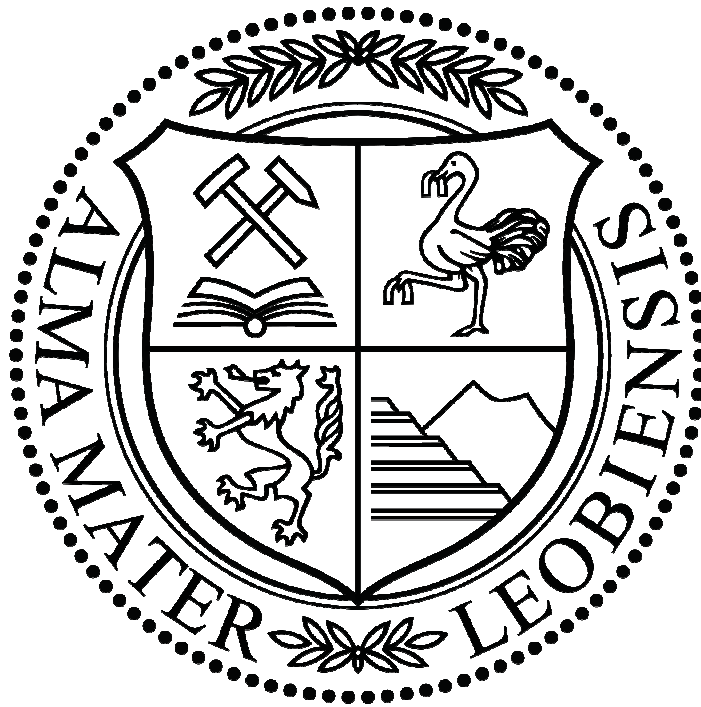


Master of Science Thesis

**Principles of benchmarking criteria
for the European Magnesia
Industry**



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Submitted to the
Department of Mineral Resources and Petroleum Engineering
Chair of Mining Engineering
University of Leoben, Austria
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Affidavit

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only the literature cited in this volume.



Mathias TROJER
Leoben, October 2009

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A. Abstract

The allocation methodology of the European Emission Trading Scheme for the third phase (2013 – 2020) regulates the allocation of certificates for all sectors, which are obliged to trade emissions in a new manner. In general, the benchmark-based method allocates green house gas allowances based on a certain amount of emissions.

Consultants developed a study about benchmarking criteria for CO₂ emissions for different industrial sectors in behalf of the European Commission.

Regarding the European Magnesia industry, which is small compared to other energy-intensive sectors, the general consultant allocation principles cannot be applied to the extent requested.

The general principles that are used in benchmarking (average of top 10% in the field) have to be adapted, as data confidentiality can not be guaranteed as a result of an exceedingly small, statistical basic set. Therefore, another option – a benchmark based on independent theoretical foundations - for the regulation of benchmark definitions for the European Magnesia industry has been chosen. This was the result of an extensive discussion about the framework.

After an in-depth look at the manufacturing processes, different specifications of magnesia will be exemplified.

In order to determine an independent technical foundation for the production of dead burned magnesia, thermo-dynamical standard works were used. The minimum theoretical energy input for the production of dead burned magnesia depends in great parts on the dissociation (Carbonate – Oxide) and the mineralogical composition of the raw material as well as the resulting sintering temperature.

A generic kiln was assumed, which can be seen as a representative for the production of DBM. It was found that the reduction potential with regards to heat losses is minimal because modern kilns are lined with high efficient insulation and refractory material. They are also optimized in construction. For the supply of the needed energy, a fuel mix consisting of fossil fuels used in the sector was adopted. Moreover, the potential of the energy content from flue gas as a result of the flue gas cleaning system was determined and the essential energy input calculated.

Taking into consideration the essential energy input and the CO₂ emission factor, which is calculated from the adopted fuel mix, the amount of CO₂ emissions per 1 ton Dead Burned Magnesia was demonstrated.

Finally, specific carbon balances were determined (generic kiln, average EU-27, operation representing a synthetic DBM production, operation based on an estimation of Chinese equipment), which reflect high differences due to fuel based CO₂ emissions.

The results of this diploma thesis can be used to create a benchmark based on energy efficiency and best practise.

B. Kurzzusammenfassung

Die europäische Emissionshandelsrichtlinie (Directive 2003/87/EC – Emission Trading Scheme) regelt die Zuteilung der Zertifikate für die emissionshandelspflichtigen Sektoren in der dritten Handelsperiode 2013 – 2020 neu. Die Zuteilung soll auf der Grundlage von Benchmarks basieren.

Ein Beratungsunternehmen im Bereich der erneuerbaren Energien und Energieeffizienz wurde von der Europäischen Kommission mit der Aufgabe betraut, Prinzipien bzw. Grundlagen zur Erstellung von allgemein gültigen Benchmarks zu entwickeln.

In Bezug auf die europäische Magnesiaindustrie, die im Vergleich zu anderen energieintensiven Industrien eine vergleichsweise geringe Anzahl an Installationen im innereuropäischen Raum aufweist, können die von der Kommission geforderten Allokationsprinzipien nicht im vollen Umfang angewendet werden.

Grund dafür ist die zu geringe statistische Grundmenge (Benchmarks richteten sich nach dem Mittelwert der besten 10% in der Branche), wodurch die Vertraulichkeit der Daten nicht gewährleistet ist. Ableitend daraus, muss die Definition von Benchmarks in Bezug auf die europäische Magnesiaindustrie auf der Grundlage unabhängiger technischer Daten basieren. Dies ist das Resultat einer ausführlichen Diskussion der legislativen Rahmenbedingungen.

Nach einem Einblick in die unterschiedlichen Herstellungsverfahren zur Erzeugung von Sintermagnesia, wird im Besonderen auch auf die unterschiedlichen Modifikationen von Magnesia eingegangen.

Um eine unabhängige technische Grundlage erstellen zu können, musste auf thermodynamische Regelwerke zurückgegriffen werden und daraus der theoretische Energiebedarf pro Tonne MgO ermittelt werden. Dieser ist abhängig von der Dissoziation (Karbonatzerfall) und von der mineralogischen Zusammensetzung bzw. der sich daraus ableitenden Sintertemperatur.

Wärmeverluste (Abstrahlungsverluste) bei der industriellen Herstellung von Sintermagnesia sind zu einem bestimmten Anteil technisch nicht reduzierbar und daher als notwendig

anzusehen. Zur Bestimmung dieser wird ein theoretisches Aggregat, das für die europäische Magnesiaindustrie als repräsentativ angesehen werden kann, herangezogen.

Daraus ergibt sich, dass Möglichkeiten von Einsparungspotenzialen in Bezug auf Wärmeverluste äußerst gering sind, da moderne Öfen mit hocheffizienten Isolierungen und technisch optimiertem Feuerfestmaterial bestückt sind.

Zur Bereitstellung der geforderten Energiemenge wurde ein realistischer Brennstoff-Mix adaptiert, der sich aus fossilen Brennstoffen zusammensetzt. Der Energieinhalt des bei der Verbrennung anfallenden Abgases wird errechnet und somit der tatsächliche Energiebedarf zur Herstellung von einer Tonne Sinter ermittelt.

Aus dem tatsächlichen Energiebedarf und dem spezifischen CO₂ Emissionsfaktor, der sich aus dem Brennstoff-Mix errechnet, werden die entstehenden CO₂ Emissionen infolge der Sintermagnesiaherstellung dargestellt.

Abschließend werden das theoretisch ermittelte Aggregat, der Durchschnitt der EU-27, ein Sintermagnesia Produzent aus einem OECD Land und ein Betrieb aus China (Abschätzung) miteinander verglichen, wobei sich deutliche Unterschiede der Brennstoff bezogenen Emissionen widerspiegelt.

Die vorliegende Diplomarbeit stellt somit eine Grundlage zur Definition von Benchmarks dar, die auf Energieeffizienz und „Best – Practice – Standards“ basiert.

1 Assignment of tasks

This diploma thesis was initiated as a result of the challenging debate on emission trading in Europe, which resulted from the Emission Trading Scheme (Directive 2003/87/EC).

Hence the European magnesia industry is comparatively small, it has to be treated differently, and general principles that are used for benchmarking (average of the 10% best performing installations) have to be adapted. This has to be done because, otherwise, data confidentiality can not be guaranteed as a result of an exceedingly small, statistical basic set.

That raises the question whether an allocation of emission rights based on benchmarks can be done besides the fact, statistical approaches cannot be used. Furthermore which criteria are decisive for developing benchmarks for the European magnesia industry?

This diploma thesis should provide an independent, theoretical and scientific foundation to develop benchmarks for the production of dead burned magnesia without the use of any statistical methods.

2 Introduction

The growing global industrialization and the associated economical processes currently have a huge impact on the environment. During the 20th century, the worldwide population growth and its wide-ranging effects have dramatically influenced this situation.

These lingering effects have been linked to higher CO₂-emissions, as evidenced by the results of numerous research projects. The atmospheric Carbon dioxide (CO₂) content is the highest among all anthropogenically caused greenhouse gases.

This is a list of the aforementioned anthropogenic greenhouse gases:

- Carbon dioxide (CO₂)
- Methane (CH₄)
- Nitrous oxide (N₂O)
- Hydrofluorocarbon (FCKW)
- Sulphur hexafluoride (SF₆)

The European commission (EC) is supposed to reduce the European greenhouse gases until 2020, to a level that is 14% lower in emissions than it was in 2005. Therefore, this goal is a great challenge for the energy-intensive industries in Europe. Taking into consideration the climate conference of 1997 in Kyoto, this is an ongoing process.

In 1997, the industrial countries committed to reduce 5.2% of the annual emissions compared to 1990. In 2002, the contract was ratified by the European Union and a general reduction of 8% on the basis of emissions measured in 1990 was decided on. As a matter of comparison, Austria intended a reduction of 13%. At the world climate conference in Bali in 2007, a new ratification was announced, which included a reduction of 20% based on the 1990 levels.¹

In order to realize this ambitious goal, the European Trading System (ETS) was founded. Furthermore, the members of the European Union had to reduce 8% of their emissions until 2012 as well as 20% until 2020, both based on the 1990 level.

As a result of this continuous process, it is very likely that further adaptations will be made. Moreover, a higher reduction could be achieved, if more industrial nations would contribute. The participation of the United States, as well as emerging markets like China and India, is necessary to achieve major reductions.²

¹ http://www.europarl.europa.eu/news/public/story_page/064-32904-182-06-27-911-20080627STO32878-2008-30-06-2008/default_de.htm (01.04.2009)

² Umweltbundesamt, Klimaschutzbericht 2009, Wien, Seite 7

This figure shows the source of greenhouse gases in the European Union (EU 27):

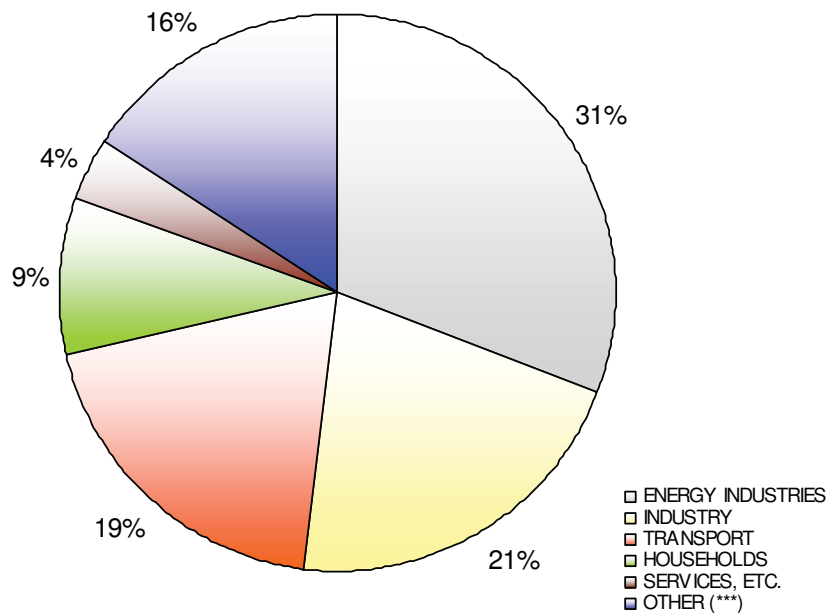


Figure 1: GHG emissions separated into different sectors (Source: European Commission, 2009³)

The basic concept of the European Trading System is to link emissions to a certain price. Thus, emissions would be banned, especially when they are unnecessary.

This trading scheme should provide the economical background to achieve the commitments of the European Union. Supporting a competitive market, several regulations have to be implemented, especially for the more energy-intensive industry.⁴ Otherwise, the whole process of reducing CO₂ would probably result in limited production, outsourcing, and undesirable economical drawbacks.

The following consequences are quite obvious:

- Loss of raw material supply from the European deposit
- Loss of profit (value creation)
- Loss of jobs within the European Union
- Global increase of Carbon dioxide Emissions – no regulations in developing countries

³ European Commission, Directorate-General for Energy and Transport, Statistical Pocketbook 2009, Seite 185

⁴ http://www.europarl.europa.eu/news/public/story_page/064-32904-182-06-27-911-20080627STO32878-2008-30-06-2008/default_de.htm (1.4.2009)

Consequently, the European Trading System established regulations to prevent such developments. Basically, with the help of a directive, the allocation of CO₂-certificates can be controlled.

Thus, different industries could be treated in a fair manner and in accordance with their production needs. If the legal principles respect particular industrial backgrounds, the European Trading System will be able to achieve its goals. In this manner, the European Union will remain an industrial location and companies will be able to rely on well-defined legal conditions.

3 Framework

3.1 The Kyoto Protocol

Greenhouse gas emissions have dramatically increased since the globalization movement started. Although a copious amount of research has been done, there are still many uncertainties about its effect on the global climate.

In 1988, at the world climate conference in Toronto, first recommendations were made to reduce greenhouse gas emissions.⁵

Moreover, in 1997, the Kyoto protocol was initialised and it forced developed, industrial countries to reduce their anthropogenic greenhouse gas (GHG) emissions.⁶

Considering the different circumstances in the participating countries, so-called Burden Sharing was used to achieve this ambitious goal. Consequently, quantified emission limitation and reduction commitments were set for every single country.

On the 4th of March 2002, the Kyoto protocol was ratified by the Council of the European Union and the members were committed to reduce 8% of the GHG emissions (based on 1990) during the first commitment period (2008 through 2012). Generally, the United Nations Framework Convention on Climate Change (UNFCCC)⁷ was the first international organisation to address this particular problem. The organisation stressed that, in contrast to developing countries, industrialised countries have financial and institutional capacities to reduce GHG emissions.

Since they are responsible for a large part of all GHG emissions, they should try to find a way to reduce them. Otherwise, they themselves will have to face the impact of those gases on the global climate.⁸

3.1.1 *Kyoto's market-based flexible mechanism*

The Kyoto Protocol introduced three market-based "flexible mechanisms":⁹

- EMISSIONS TRADING
- JOINT IMPLEMENTATION
- CLEAN DEVELOPMENT MECHANISM

⁵ cp. <http://www.agenda21-treffpunkt.de/thema/kyoto-protokoll.htm>, 15.5.2009

⁶ Mustafa H. Babiker (2004): Climate Change policy, market structure, and carbon leakage,

⁷ <http://unfccc.int>

⁸ cp. Drnek, Maier (2003), BHM – Berg und Hüttenmännische Monatshefte, Wien

⁹ <http://europa.eu/rapid/pressReleasesAction.do?reference=MEMO/03/154&format=HTML&aged=1&language=en&guiLanguage=en>

Emission Trading

“All parties with commitments under the Kyoto Protocol have accepted targets for limiting or reducing GHG emissions. These targets are expressed as levels of allowed emissions, or assigned amounts, over the 2008-2012 commitment period. Emission Trading¹⁰ allows countries that have emission units to spare to sell this excess capacity to countries that are over their targets.”¹¹ The theoretical concept of Emission Trading is based on the Coase theorem, named after the American economist Ronald Harry Coase.

“Coase theorem asserts that as long as there are well-defined property rights (and no transaction costs), externalities will not cause a breakdown in the allocation of resources. Externalities being defined as the benefits or costs to a society of the process of consumption or production.”¹²

The permission for CO₂-emissions is dealt on standardized stock-markets.¹³

Joint Implementation (JI)

Joint Implementation offers a business an opportunity to earn emission reduction units from an emission reduction project done in another Annex B¹⁴ country. JI is defined in Article 6 of the Kyoto Protocol. On the one hand, it exhibits benefits from foreign investments and technology transfer to the host party and, on the other hand, it is flexible as far as fulfilling reduction commitments under the Kyoto Protocol.¹⁵

Clean Development Mechanism (CDM)

Annex B parties (countries) and companies do have the opportunity to implement an emission-reduction project in developing countries. These projects can earn viable, certified emission reduction credits; an example would be the installation of a power plant by using alternative energy sources. The reason for using the CDM is to stimulate a sustainable development to go along with the reduction of GHG emissions.¹⁶ The methodology and the corresponding directive is decided by the CDM executive council. This council is made up of ten parties, four of which represent industrialized countries and six that represent emerging markets. In general, the Clean Development Mechanism is very complex and cost-intensive. In reference to the European magnesia industry, the administrative effort is clearly disproportionate when compared to the GHG reduction potential.

¹⁰ Kyoto Protocol of the United Nations Framework Convention on Climate Change, Article 17

¹¹ http://unfccc.int/kyoto_protocol/mechanisms/emissions_trading/items/2731.php

¹² <http://www.economyprofessor.com/economictheories/coase-theorem.php>

¹³ cp. Drnek, Maier (2003), BHM – Berg und Hüttenmännische Monatshefte, Wien

¹⁴ Annex B summarizes all parties with commitments under the Kyoto Protocol to reduce the GHG emissions

¹⁵ http://unfccc.int/kyoto_protocol/mechanisms/joint_implementation/items/1674.php

¹⁶ http://unfccc.int/kyoto_protocol/mechanisms/clean_development_mechanism/items/2718.php

3.2 The European Union Emission Trading Scheme (EU-ETS)

To achieve all the commitments made under the Kyoto Protocol, the European Union (EU) developed its own Emission Trading Scheme. On July, 2nd 2003, the European Parliament established the “Directive 2003/87/EC”, a scheme for GHG emission allowances trading within the community. The main target is to reduce emissions in a cost-effective and economically efficient manner.¹⁷

Basically, the EU ETS could also be designated as a “Cap and Trade System”, which is characterized as following:¹⁸

- Limited CO₂ emissions (Cap)
- Tradable certificates covering the annual CO₂ emissions
- Certificates need to be purchased for emitted GHG emissions

The EU ETS determines the reduction of GHG emissions, which on a European level is further passed down to the various sub-sectors (to be precise, the energy-intensive sectors of the industries). The number of certificates (CO₂ equivalent) depends on the industrial sector, the size of the installation and, in fact, the amount of emitted GHG emissions. The European Union defines the number of GHG emission allowances for the entire period. Every single certificate authorizes a company to emit a certain amount of GHG emissions, which means that emitting GHG emissions without an according certificate (CO₂ equivalent) is impossible.¹⁹ The cost of the GHG emission allowances, therefore, depends on the supply and demand on the market.

The first of three periods of the EU ETS started on January 1st, 2005 and focused on CO₂ emissions only. The currently ongoing second period started in 2008 and will continue until 2012. The list of GHG emissions was extended, as can be seen from this list:

- Carbon dioxide (CO₂)
- Methane (CH₄)
- Nitrous Oxide (N₂O)
- Hydrofluorocarbons (HFCs)
- Perfluorocarbons (PFCs)
- Sulphur Hexafluoride (SF₆)

¹⁷ European Union (2003): Direktive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community

¹⁸ cp. <http://www.germanwatch.org/foalien/eu-et/foalie015.htm>, 11.Mai.2009

¹⁹ cp. <http://www.setatwork.eu/trading.htm>

The European Union ratified the Kyoto Protocol in order to reduce GHG emissions by about 8% (based on 1990 levels) until 2012 and the EU revised the reduction value to 20% (30% in the event of an international agreement) until 2020 at the world climate conference in Bali in 2007.

The post-Kyoto goal set by the European Union is to reduce the GHG emissions by about 20% (based on the 1990 levels), if there is no international agreement decided upon on December 15th, 2009 in Copenhagen.²⁰

Every year a reduction factor of 1.74 will reduce the GHG emissions from 2,083 million tons per year in 2013 to 1,720 million tons in 2020. If a satisfying agreement on an international level is made, the European Union will increase the GHG reduction goal up to 30% until the year 2020.²¹ An abundance of information regarding the European Union Emission Trading Scheme can be found and downloaded from the official homepage of the European Union.²²

3.3 Area of application of the Emission Trading Scheme (EU-ETS)

The scope of this directive - *DIRECTIVE 2003/87/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC – is:*²³

Article I, RL 2003/87/EC

Subject matter

“This Directive establishes a scheme for greenhouse gas emission allowance trading within the Community (hereinafter referred to as the ‘Community scheme’) in order to promote reductions of greenhouse gas emissions in a cost-effective and economically efficient manner.”²⁴

Article II, RL 2003/87/EC

Scope

1. *“This Directive shall apply to emissions from the activities listed in Annex I and greenhouse gases listed in Annex II.*
2. *This Directive shall apply without prejudice to any requirements pursuant to Directive 96/61/EC.”²⁵*

²⁰ Homepage of the European Parliament: http://ec.europa.eu/environment/climat/emission/2nd_phase_ep.htm

²¹ Homepage of the European Parliament, I.c.

²² Homepage of the European Parliament, I.c.

²³ European Union (2003): DIRECTIVE 2003/87/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, Brussels, Article I, II

²⁴ European Union (2003)

3.3.1 *Effect of the Directive 2003/87/EC on the European Magnesia Industry*

The raw material used for the production of great variety of refractory products is called Dead Burned Magnesia (DBM). Producing DBM is very energy-intensive and a large amount of the CO₂ emission occurs as a result of the dissociation of carbonate and the heat treatment of oxide. Due to the high amount of process-related emissions, the Magnesia industry must be considered CO₂-intensive. Moreover, the whole industry is massively involved in global competition (Tradintensity 68%-statement RHI AG). As chapter 6 describes, there are only a few ways to reduce CO₂ emissions in connection with the production process. On an international level, there is a significant competitive disadvantage for the European magnesia industry as a result of directive 2003/87/EC. The challenge is that additional costs (approximately 25% additional costs for an average CO₂ certificate price of 30 €/t CO₂) cannot be passed on to the customers. Consequently, competitors without any comparable commitments have a decisive advantage on the market.

Carbon Leakage

Carbon leakage (CL) describes a phenomenon, which is defined as an increase in emissions outside of a region as a direct result of the “European Emission Trading Scheme” (whose goal it is to cap emissions in that region).²⁶ Therefore, emissions will be reduced within the EU, but, simultaneously, the turnover and the number of employees will shrink dramatically.

“Because of the close connection between CO₂ emissions and fossil fuel use, countries that want to pursue a more restrictive policy with respect to their emissions worry that their energy-intensive industries will suffer from international competition from industries in countries that follow a laxer climate change policy.”²⁷

The CL issue was already known (“pollution haven”, “race to the bottom”) when discussions on globalization started at the end of the 20th century. A general tendency is to outsource production to the most providential location. The “pollution haven” hypothesis argues that highly pollution-intensive industry has been migrating from developed economies to developing countries because of the strict environmental regulations and the increasing production costs.²⁸

At the same time, developing countries with low wages and lax environmental restrictions provide an incentive for this kind of industry. On the other hand, developing countries are allocated financial resources.

²⁵ European Union (2003)

²⁶ http://www.iea.org/textbase/papers/2008/Aluminium_EU_ETS.pdf

²⁷ Reyer Gerlagh and Onno Kuik (2007): Carbon Leakage with International Technology Spillovers

²⁸ <http://ideas.repec.org/p/met/wpaper/0403.html>

It is quite possible that developing countries continue to reduce their environmental restrictions in order to be considered a lucrative location for new investments (“race to the bottom”). Therefore, irreversible damage is caused to the environment, which all nations have to suffer (a so-called “Tragedy of the Commons”).²⁹

At the United Nations Climate Change Conference (Dec. 2009) in Copenhagen, an agreement that focuses on climate change is going to be discussed. Expectations for this conference are high, thanks to the firm stand taken by the US at the G8 SUMMIT in L’Aquila (Italy) in 2009.³⁰ The role of the emerging markets, however, remains problematic and afflicted with numerous uncertainties. The EU has its own, independent agenda against climate change. The CL problem was discussed when the directive 2003/87/EC became effective. A decision was made that particularly energy-intensive industry (higher risk of Carbon Leakage) should be protected through the free allocation of certificates.

3.3.2 Legal agreement based on the EU Directive 2003/87/EC

Article 10a, paragraph 12 - 17 as well as Article 10b, paragraph 1 and 2 Directive 2003/87/EC refer to the Carbon Leakage problem. Regarding article 10a Directive 2003/87/EC, all installations and sectors put at risk of carbon leakage receive free allocation in the third period (2013-2020). The allowable amount of certificates is going to be up to 100% and will be assigned on the basis of benchmarks, as well as grandfathering.³¹ In the case that 100% of freely allocated certificates are not sufficient for the carbon leakage-endangered industry, a correction factor will be established.

Article 10a paragraph 14, directive 2003/87/EC

“In order to determine the sectors or sub-sectors referred to in paragraph 12, the Commission shall assess, at Community level, the extent to which it is possible for the sector or sub-sector concerned, at the relevant level of disaggregation, to pass on the direct cost of the required allowances and the indirect costs from higher electricity prices resulting from the implementation of this Directive into product prices without significant loss of market share to less carbon efficient installations outside the Community.”

²⁹ Deutsche Emissionshandelsstelle (DEHSt) im Umweltbundesamt (2008): CARBON LEAKAGE DIE VERLAGERUNG VON PRODUKTION UND EMISSIONEN ALS HERAUSFORDERUNG FÜR DEN EMISSIONSHANDEL, Seite 5

³⁰ Official homepage of the G 8 summit – July 2009: <http://www.g8italia2009.it>

³¹ Grandfathering: When rules are changed, allowing actions taken before a certain date to remain subject to the old rules. For example, Congress may change the law by stipulating that certain types of municipal bonds no longer pay tax-free interest, while at the same time grandfathering the municipal bonds issued before the date on which the new law is to take effect. <http://www.yourdictionary.com/business/grandfathering>

*These assessments shall be based on an average carbon price according to the Commission's Impact Assessment accompanying the Package of Implementation measures for the EU's objectives on climate change and renewable energy for 2020 and, if available, trade, production and value added data from the three most recent years for each sector or sub-sector.*³²

Carbon leakage classification data is based on the NACE-3/4 code, which, in the case of magnesia, is 08.99 (in the literature it is often 14.50 – representing the old NACE code). The criteria for registration in the carbon leakage directory are found in **Article 10a, paragraph 15 (Directive 2003/87/EC)**.

*"A sector or sub-sector shall be deemed to be exposed to a significant risk of carbon leakage if:*³³

- (a) the sum of direct and indirect additional costs induced by the implementation of this Directive would lead to a substantial increase of production costs, calculated as a proportion of the gross value added, of at least 5 %; and*
- (b) the intensity of trade with third countries, defined as the ratio between the total value of exports to third countries plus the value of imports from third countries and the total market size for the Community (annual turnover plus total imports from third countries), is above 10%.*

$$\text{Tradeintensity} = \frac{\text{Total value of export to third countries} + \text{Total value of imports from third countries}}{\text{Total market size for the Community (annual turnover} + \text{total imports from third countries)}}$$

“

A sector is at risk of carbon leakage, if both criteria are fulfilled or if one of the numerical terms exceeds 30% (cf. Article 10a paragraph 16 Directive 2003/87/EC).

³² European Union (2003): The European Parliament, Brussels, Directive of the European Parliament and Council amending Directive 2003/87/EC, Artikel 10a, Absatz 14; http://ec.europa.eu/environment/climat/emission/ets_post2012_en.htm

³³ European Union, The European Parliament, Brussels, l.c. Article 10a. paragraph 15

Article 10a paragraph 16 Directive 2003/87/EC

“The list referred to in paragraph 13 may be supplemented after completion of a qualitative assessment, taking into account, where the relevant data are available, the following criteria.”³⁴

- (a) the extent to which it is possible for individual installations in the sector or sub-sector concerned to reduce emission levels or electricity consumption, including, as appropriate, the increase in production costs that the related investment may entail, for instance on the basis of the most efficient techniques;*
- (b) current and projected market characteristics, including when trade exposure or direct and indirect cost increase rates are close to one of the thresholds mentioned in paragraph 16*
- (c) profit margins as a potential indicator of long-run investment or relocation decisions.”*

Article 10a paragraph 18 Directive 2003/87/EC

“The list referred to in paragraph 13 shall be determined after taking into account, where the relevant data are available, the following.”³⁵

- (a) the extent to which third countries, representing a decisive share of global production of products in sectors or sub-sectors deemed to be at risk of carbon leakage, firmly commit to reducing greenhouse gas emissions in the relevant sectors or sub-sectors to an extent comparable to that of the Community and within the same time frame, and*
- (b) the extent to which the carbon efficiency of installations located in these countries is comparable to that of the Community.”*

The register of the carbon leakage classified sectors and sub-sectors have to be confirmed by the European Commission and Council until 31st December 2009. This register is going to be adapted every five years.

³⁴ European Union, The European Parliament, Brussels, I.c. Article 10a. paragraph 17

³⁵ European Union, The European Parliament, Brussels, I.c. Article 10a. paragraph 18

The European Community, or rather every individual member state, has the chance to nominate a sector or sub-sector for the carbon leakage register, if a technical report corroborates that the necessary criteria for its registration have been fulfilled.

Article 10b paragraph 1 Directive 2003/87/EC

“Measures to support certain energy-intensive industries in the event of carbon leakage.”³⁶

By 30 June 2010, the Commission shall, in the light of the outcome of the international negotiations and the extent to which these lead to global greenhouse gas emission reductions, and after consulting with all relevant social partners, submit to the European Parliament and to the Council an analytical report assessing the situation with regard to energy-intensive sectors or sub-sectors that have been determined to be exposed to significant risks of carbon leakage.

This shall be accompanied by any appropriate proposals, which may include:

- (a) adjustment of the proportion of allowances received free of charge by those sectors or sub-sectors under Article 10a;*
- (b) inclusion in the Community scheme of importers of products which are produced by the sectors or sub-sectors determined in accordance with Article 10a;*
- (c) assessment of the impact of carbon leakage on Member States' energy security, in particular where the electricity connections with the rest of the Union are insufficient and where there are electricity connections with third countries, and appropriate measures in this regard.*

Any binding sectoral agreements which lead to global greenhouse gas emissions reductions of the magnitude required to effectively address climate change, and which are monitorable, verifiable and subject to mandatory enforcement arrangements shall also be taken into account when considering what measures are appropriate.”

³⁶ European Union, The European Parliament, Brussels, I.c. Article 10b. paragraph 1

3.3.3 Benchmarks – criteria for developing benchmarks

Basic considerations of Benchmarking

In general, benchmarking is a continuing process of comparing different products (services), processes and methods of a company with the best competitor in the field. The main objective is to close the gap to the BEST PERFORMER. It is an efficient instrument in competition analysis to determine a company's exact position on the global market.³⁷

Robert Camp, the actual founder of benchmarking, defines it as *“the continuous process of measuring our products, services, and practices against our competition or leading-edge companies.”*³⁸

In case of developing benchmarks, it is crucial to analyze whichever competitor deserves to be characterized as BEST IN PRACTICE or BEST PERFORMER. Typically, benchmarking orientates itself with respect to the BEST AVAILABLE TECHNOLOGY of the time and, therefore, it helps set trends regarding the efficiency of technology used. Thus, benchmarks can have a stimulating effect in the use of low-emission techniques and fuels for production processes.

The most salient characteristics of benchmarking are already mentioned in the definition of benchmarking.³⁹

- **Best Available Technology (BAT):** analysis of all competitors in the entire industry and aspiring towards the BEST in CLASS.

The biggest disadvantage of benchmarking with regards to the Directive 2003/87/EC is the expenditure of time, since the overwhelming number of production processes leads to an enormous administrative workload due to the sheer number of benchmarks.

In **Article 10a paragraph 1 Directive 2003/87/EC** is mentioned, *“that on 31st December 2010, the Commission shall adopt Community-wide and fully-harmonized implementing measures for the allocation of the allowances, including any necessary provisions for a harmonized application.”*⁴⁰

³⁷ cp. www.4managers.de/themen/benchmarking/ ; 16.03.2009

³⁸ <http://www.well.com/~bbear/camp.html>

³⁹ cp. <http://www.benchmarking.de/info/bm-info/definition>

⁴⁰ European Union, The European Parliament, Brussels, I.c. Article 10a. paragraph 1

Those measures, designed to amend non-essential elements of this Directive by supplementing it, shall be adopted in accordance with the regulatory procedure with scrutiny.

The measures shall, to the extent feasible, determine Community-wide ex-ante benchmarks⁴¹ so as to ensure that allocation takes place in a manner that provides incentives for reductions in greenhouse gas emissions and energy efficient techniques, by taking account of⁴²

- *the most efficient techniques,*
- *substitutes,*
- *alternative production processes,*
- *high efficiency cogeneration,*
- *efficient energy recovery of waste gases, use of biomass and capture and storage of CO₂, where such facilities are available,*

and shall not provide incentives to increase emissions. No free allocation shall be made in respect of any electricity production, except for cases falling within Article 10c and electricity produced from waste gases.

For each sector and sub-sector, in principle, the benchmark shall be calculated for products rather than for inputs, in order to maximize greenhouse gas emissions reductions and energy efficiency savings throughout each production process of the sector or the sub-sector concerned.”⁴³

Benchmarks regarding to the Directive 2003/87/EC

During the first and the second period of the European Emission Trading Scheme (EU ETS), most member states used benchmarks for new entrant allocation in the industrial sector and some used benchmarks for already existing installations.⁴⁴

No unitary standard existed, which could have helped define fully-harmonized benchmarks and, additionally, benchmarking approaches did not converge from period I to period II within the European Community. In most cases, the “Best Available Techniques Reference documents” (BREFs) were used as a basis for the definition of a benchmark. However, with regards to the sectors and sub-sectors, the benchmarks’ levels differed strongly as far as the detail and stringency of the included GHG efficiency values.

Therefore, ECOFYS⁴⁵ decided that benchmarks for allocation allowances should not be based on BREF-documents in the framework of the EU ETS.⁴⁶

⁴¹ Ex-ante Benchmark is based on a study done for economical interests in advance

⁴² European Union, The European Parliament, Brussels, I.c. Article 10a. paragraph 1

⁴³ European Union, The European Parliament, Brussels, I.c. Article 10a. paragraph 1

⁴⁴ ECOFYS (2009): Developing benchmarking criteria for CO₂ emissions, Netherlands, p.III

Allocation principles

“A benchmark based allocation methodology requires several choices, e.g. on⁴⁷

- The number of products to distinguish*
- The emissions the benchmark relates to: only direct emissions or also the indirect emissions from electricity use*
- The benchmark for the specific energy consumption for a certain product*
- The benchmark for the fuel mix that is used to produce a certain product*
- The inclusion of correction factors for e.g. different technologies used or the size of the installation*
- The production (activity) levels that is used to convert the benchmarks (specific emission per unit of production) to an absolute emission allowance”*

In the study **“Developing benchmarking criteria for CO₂ Emissions”⁴⁸**, eleven allocation principles were formulated that *“could form a basis for a benchmark-based allocation methodology”⁴⁹*. The following principles are taking into account that *“ex-ante allocation of allowances for direct emissions within a certain emission cap and without free allocation to any electricity production”⁵⁰*.

- 1. Base the benchmark level on the most energy efficient technology*
- 2. Do not use technology-specific benchmarks for technologies producing the same product*
- 3. Do not differentiate between existing and new plants*
- 4. Do not apply corrections for plant age, plant size, raw material quality and climatic circumstances*
- 5. Only use separate benchmarks for different products if verifiable production data is available based on unambiguous and justifiable product classifications*
- 6. Use separate benchmarks for intermediate products if these products are traded between Installations*
- 7. Do not use fuel-specific benchmarks for individual installations or for installations in specific countries*

⁴⁵ ECOFYS - research and consultancy on renewable energy, energy savings and climate policies.

⁴⁶ ECOFYS (2009), I.c., p.III

⁴⁷ ECOFYS (2009), I.c., p.III

⁴⁸ ECOFYS Netherlands and The Fraunhofer Institute for Systems and Innovation research

⁴⁹ ECOFYS (2009), I.c., p. IV

⁵⁰ ECOFYS (2009), I.c., p. IV

8. *Take technology-specific fuel choices into account in determining benchmarks*
9. *Use historical production to allocate allowances for existing installations*
10. *Use product-specific capacity utilization rates in combination with verifiable capacity data to allocate allowances to new installations*
11. *Use heat production benchmark combined with a generic efficiency improvement factor for heat consumption in processes where no output-based benchmark is developed*

Principle 1 – Most energy efficient technology as basis for benchmark

“The choice for most energy efficient technology as basis for the benchmark allows the use of the same benchmark for both existing and new installations and is also well in line with the proposal for a revised directive where explicit reference is made to most efficient technology. Furthermore, it puts the benchmarks for the different products at the same reference level. This is advantageous in view of the uniform correction factor foreseen by the European Commission to bring the sum of allowances within the total available emission cap. The benchmark for one product influences in this way, via the correction factor, the allowance for another product. This requires a uniform reference level for the benchmarks.”⁵¹

Principle 2, 3, 4 and 7 – Do not specify the benchmark in too much detail

“The objective of the EU ETS is to give incentives for GHG efficient technologies. Ideally, a benchmark-based allocation methodology should thus provide incentives for companies to select the most cost-effective emission reduction options available. Such incentives are removed when a single product with a single benchmark (principle 2) is further specified into products that can be produced with different techniques and fuel mixes (principle 2 and 7) or by installations with a different size or age (principle 3 and 4), each having their own benchmark.”⁵²

Principle 5 and 6 – Number of products to distinguish

“Principle 1 leaves the definition of “the same product” open. Criteria that can be used to establish the number products to distinguish include the availability of the relevant production data and the difference in emission intensity between the different products. We regard the availability of production data following unambiguous and justifiable product classifications as

⁵¹ ECOFYS (2009), l.c., p. IV

⁵² ECOFYS (2009), l.c., p. V

indispensable (principle 5), but do not further recommend general allocation principles for the number of products to distinguish. To allow determining an allocation of allowances also for those installations producing intermediate products sold to other EU ETS installations, we recommend having separate benchmarks for these traded intermediates (principle 6).⁵³

Principle 7 – Fuel mix benchmark

“Various options exist for the choice of fuel mix (e.g. average fuel mix of the sector, best practice fuel mix, most dominant fossil fuel). Given the strong political dimension of the fuel mix choice we did not formulate an allocation principle on this issue. As allocation principle we do recommend, however, not to distinguish the fuel mix benchmark for individual installations or for individual countries (principle 7).

In some cases, the most energy efficiency technology for a certain product implies an inherent choice for a certain fuel mix. An example is the use of biomass which is inherent to pulp making. We do recommend taking into account technology-specific fuel mix choices in determining the benchmarks (principle 8).⁵⁴

Principle 9 and 10 – Choice of activity level to convert the benchmark to an allowance

“The use of historical production in determining allowances to existing installations (principle 9) has as advantage that no data are required on capacity of installations or on subjective assumptions regarding sector growth. These advantages in our opinion outweigh potential advantages of other methodologies. For new installations, where historical production is not available, we recommend product-specific capacity utilization rates in combination with verifiable capacity data (principle 10).⁵⁵

Principle 11 – What if benchmark based on production is not available

“A complication arises for those situations where an output-based benchmark is not available, because of the limited amount of producers or the difficulty of determining output for some installations. For those products, a generic efficiency improvement factor could be used in combination with a benchmark based on the production of heat (principle 11). Options to derive such a generic factor include a factor based on average improvement potentials for other products or on technical analyses of the improvement potential.⁵⁶

⁵³ ECOFYS (2009), l.c., p. V

⁵⁴ ECOFYS (2009), l.c., p. V

⁵⁵ ECOFYS (2009), l.c., p. V

⁵⁶ ECOFYS (2009), l.c., p. V

3.3.4 Benchmark design with respect to the European Magnesia industry

In general, the benchmark (BM) for the “Emission Trading Scheme” was defined as the average value of the top 10% of performers in each sector or sub-sector.

Regarding the directive 2003/87/EC, the allocation methodology is based on benchmarks. ECOFYS NETHERLANDS was instructed by the European Commission in the development of a benchmark-based allocation methodology (11 allocation principles), which should be generally adaptable to all sectors and sub-sectors. In this particular study (“Developing benchmarking criteria for CO₂ emissions”), allocation principles are tested and applied to four specific industry sectors (Iron and Steel, Pulp and Paper, Lime, Glass) to evaluate their feasibility.⁵⁷

But these industries are not comparable with the magnesia industry. Therefore this diploma thesis should form the basis of a benchmark design for the European Magnesia industry in the style of the formulated benchmark-based allocation methodology done by ECOFYS.

Allocation in general

In order to implement a fully harmonized allocation methodology for all sectors and sub-sectors affected by the EU ETS, a general approach was developed by the ECOFYS.

$$\text{Allocation}^{(1)} = \text{Activity Level}^{(2)} * \text{BM}^{(3)}$$

With:

Allocation (1) = Allocation of allowances given out for free in t CO₂ / year

Activity level (2) = Activity level the benchmark refers to (e.g. t product / year)

Benchmark (3) = Benchmark for the activity indicator (e.g. t CO₂ / t product)

To come to an allocation (1) based on benchmarking, the level of a certain activity (2) needs be combined with a specific emission benchmark for this activity (3). The emission benchmark is dependent on choices related to energy efficiency, fuel mix and the treatment of process emissions.⁵⁸

$$\text{BM}^{(3)} = \text{BM}_{\text{energy efficiency}}^{(4)} * \text{BM}_{\text{fuel mix}}^{(5)} + \text{BM}_{\text{process emissions}}^{(6)}$$

⁵⁷ ECOFYS (2009), l.c., p. 33

⁵⁸ ECOFYS (2009), l.c., p. 33

With:

BM_{energy efficiency}⁽⁴⁾ = Benchmark for energy efficiency of the activity indicator (e.g. GJ / t product)

BM_{fuel mix}⁽⁵⁾ = Benchmark for the fuel mix used (e.g. t CO₂ / GJ)

BM_{process emissions}⁽⁶⁾ = Benchmark for non-fuel related process emissions (e.g. t CO₂ / t product)

The key fact is that the total amount of allowances allocated within the EU ETS needs to stay under a certain cap. Therefore, a correction factor will be introduced, if GHG emissions exceed a certain limit (cap).⁵⁹

ECOFYS recommends the three following methods for deriving the energy efficiency BM:⁶⁰

1. *A comparison of existing installations. All installations are represented on a benchmark curve and the energy benchmark level is chosen as the performance of e.g. the installation representing the 10% best installations or top quartile.*
2. *An external reference based on the available technological options. The benchmark level can, for instance, be chosen as the emissions of the most energy-efficient technology.*
3. *An external reference based on thermodynamic considerations. The energy benchmark level can for example be based on the thermodynamic minimum energy required for a certain process step.*

In order to apply all of these general principles, it is crucial to define what is considered the most energy-efficient technology or production process within the European Community.

“As source for specific energy consumption values of the most energy efficient technologies that are applied at an industrial scale, use can be made of:

- *Public literature such as the BREFs and other sources*
- *Industrial data collection efforts, i.e. existing benchmark curves*
- *Data from technology suppliers*
- *Data from specialised consultants, as far as transparency and confidentiality issues can be solved*
- *(Independently verified) data collected from operators*⁶¹

⁵⁹ ECOFYS (2009), l.c., p. 34

⁶⁰ ECOFYS (2009), l.c., p. 36

Benchmarks for the European Magnesia Industry

The European magnesia industry is comparatively small (number of installations within the European Community), when compared to other sectors of the industry. As a result, a generally applicable benchmark-based allocation methodology (ECOFYS) is not adaptive to the European Magnesia industry (average of the 10% BEST PERFORMERS). Data confidentiality could not be guaranteed as a result of this small statistical basic set. Since the required number (2) of benchmarks for the Magnesia industry is low and covers the whole sector, it seems more reasonable to develop benchmarks based on additional criteria.

In particular, allocation principles 1, 2 and 3 are going to be applied to define a benchmark for the European Magnesia industry:

1. *Base the benchmark level on the most energy efficient technology*
2. *Do not use technology-specific benchmarks for technologies producing the same product*
3. *Do not differentiate between existing and new plants*

For objective benchmarking procedures some underlying data needs to be known first, such as:

- production process
- production machinery
- amount of energy required
- amount of energy applied
- emissions

This means that the baseline of different installations and the various production processes needs to be determined and analyzed.

Fuel-mix specific benchmarks with reference to the European Magnesia Industry

The fuel-mix in the production of “dead burned magnesia” differs greatly within the European Community. This is, primarily, a result of the varying availability of different fossil fuels among member states.⁶² Therefore, ECOFYS recommends not to establish a fuel-mix benchmark for individual installations or for individual member states.⁶³

Allocation principle 7: Do not use fuel-specific benchmarks for individual installations or for installations in specific countries

⁶¹ ECOFYS (2009), l.c., p. 37

⁶² In case of the high thermodynamically energy input for producing Dead burned magnesia fossil fuels are essential.

⁶³ ECOFYS (2009), l.c., p. V

ECOFYS recommends that energy efficiency pertaining to all sorts of production processes be of major importance. This recommendation is taken into account in this paper. Table 1 represents the most significant fossil fuels, heat values and emission factors.

	net caloric value		emission factor	
	H _u	unit	EF	unit
Anthracite	28,50	[GJ/t]	95,0 ¹⁾ 94,0 ²⁾	[tCO ₂ /TJ]
Brown coal	9,70	[GJ/t]	110,0 ¹⁾ 97,0 ²⁾	[tCO ₂ /TJ]
Brown coal briquet	19,30	[GJ/t]	97,0	[tCO ₂ /TJ]
Coke	28,20	[GJ/t]	104,0	[tCO ₂ /TJ]
Residual fuel oil	40,30	[GJ/t]	80,0 ¹⁾ 78,0 ²⁾	[tCO ₂ /TJ]
Light fuel oil	41,30	[GJ/t]	78,0	[tCO ₂ /TJ]
Fuel oil	41,70	[GJ/t]	77,0 ¹⁾ 78,0 ²⁾	[tCO ₂ /TJ]
Extra light fuel oil	42,70	[GJ/t]	75,0	[tCO ₂ /TJ]
Diesel (for static installations)	42,80	[GJ/t]	73,7	[tCO ₂ /TJ]
Natural gas	36,00	[GJ/t]	55,4	[tCO ₂ /TJ]
Liquefied gas	46,00	[GJ/t]	64,0	[tCO ₂ /TJ]

¹⁾ Emission factors for power plants and for district heating plants

²⁾ Emission factors for industrial plants

Table 1: Most common fossil fuels (Source: Bundesgesetzblatt Rep. Austria 2007, 339. Verordnung: ÜBPV)

CO₂ emissions
(net caloric value pertaining on natural gas = 100%)

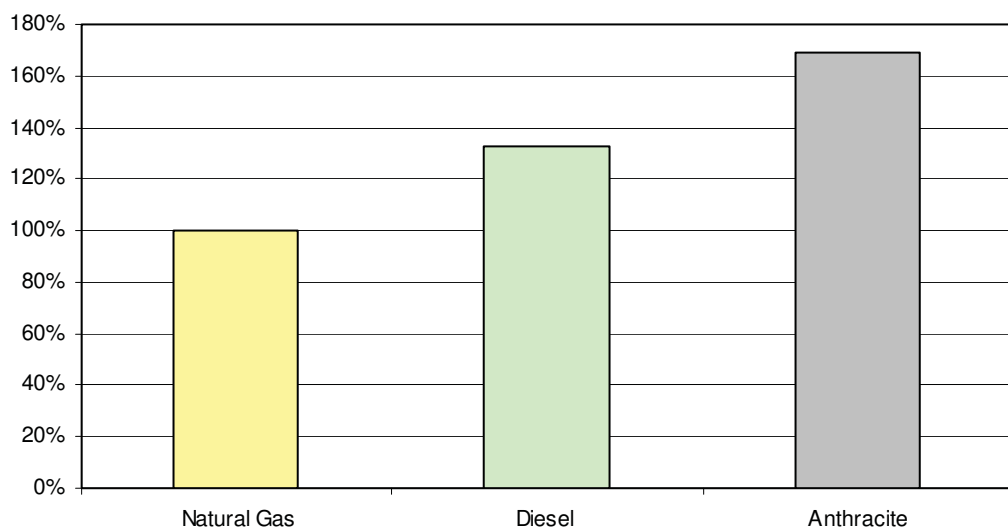


Figure 2: Arrangement of fossil fuels pertaining to their accumulating CO₂ emissions

As fig.2 illustrates, there is a sizeable difference regarding CO₂ emissions. Preferably, natural gas should be used. It must be remembered, however, that not all fossil fuels are available in all of the member states of the European Union. For this reason, low-emission fossil fuels (i.e. natural gas) can not always be used as a first choice.

Proposition for defining a benchmark for the European Magnesia Industry

Using the benchmark-based allocation methodology (ECOFYS), there exist different options for the regulation of benchmark definitions for the European Magnesia Industry.

- 1. Benchmark based on 11 allocation principles developed by ECOFYS**
- 2. Benchmark based on independent theoretical foundations**

Option 1 has to be discarded, because data confidentiality could not be guaranteed – the low number of installations within the EU results in a markedly small statistical basic set.

This diploma thesis is based on independent, theoretical foundations. It is comprised of unavoidable emissions as well as fuel-based emissions resulting from the theoretical energy input. Furthermore, marginal losses are determined with reference to the “BAT reference document” and results are compared to real production data obtained from European manufacturers.

4 Economic and technological importance of Magnesite or rather magnesia

4.1 Magnesite

Generally magnesite is identified as magnesium carbonate ($MgCO_3$), which contains 47,6% MgO and 52,4% CO_2 .⁶⁴ *“In nature there is a continuous series of different compounds of variable composition from $MgCO_3$ to Fe_2O_3 . The color of magnesite is white and with a grayish or yellowish tint and sometimes snow-white with a glassy luster. The Mohs hardness is 4,5 – 5 and the density 2,9 – 3,1 g/cm^3 . Dolomite, quartz, talc, calcite, pyrite, and other minerals are present in magnesite rock as mineral impurities.”*⁶⁵ In European magnesite deposits, the mineral is often found with dolomite in greywacke. Depending on the amount of Fe in the mineral, two different types of magnesite are distinguished:

- **Crystalline Magnesite:** Fe_2O_3 content is between 1 – 8%; encountered along with with dolomite or lime rocks; characterized by crystal faces.⁶⁵
 - **Deposits:** The most characteristic deposits are found in Austria (Breitenau, Radenthein, Veitsch), Slovakia, Spain, Russia (Satka), China, Brasil, USA, Korean Peoples' Democratic Republic
- **Microcrystalline Magnesite:** Microcrystalline (amorphous) deposits occur as products of the decomposition of ultra basic rocks; Fe_2O_3 content is <0,5%;⁶⁵
 - **Deposits:** This kind of raw material is found in Greece, Turkey, Yugoslavia, India, Saudi Arabia and Guatemala.

⁶⁴ Raw Materials, The market for Magnesia Raw Material; Eastern Refractory Institute, Shiber Corporation; Translated from Ogneupory, Vol. 34, No.11, November 1993, Seite 18-24

⁶⁵ Raw Materials, The market for Magnesia Raw Material; Eastern Refractory Institute, Shiber Corporation; Translated from Ogneupory, Vol. 34, No.11, November 1993, Seite 18-24

4.2 Magnesite Industry worldwide

Over the past 20 years, there has occurred a significant fluctuation within the magnesite production on the global market. Lowest production levels were reached in 1993 as a result of the Comecon breakdown (basically all communist countries except China).⁶⁶ Fig.3 shows the raw magnesite production worldwide over the past 100 years.

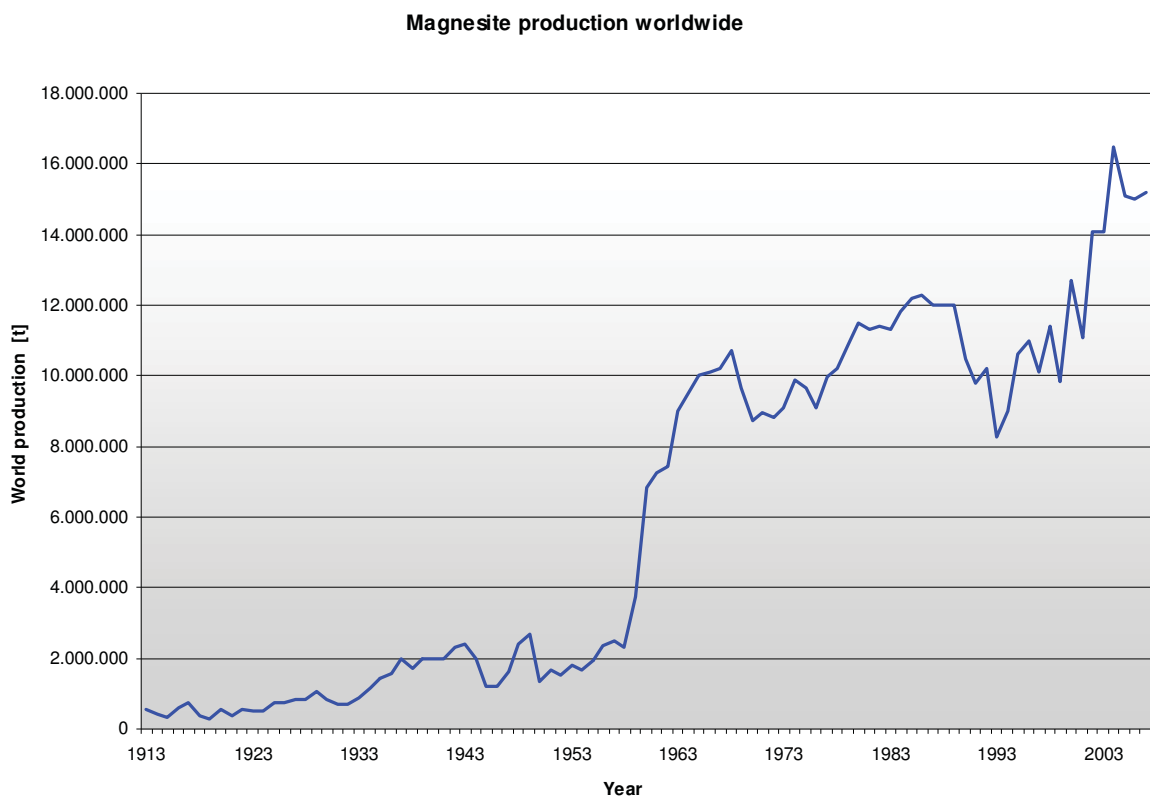


Figure 3: Raw magnesite production over the past 100 years (Source: USGS 2005)

⁶⁶ Drnek T. (2002): Die Sintermagnesia im Spannungsfeld von technologischen und wirtschaftlichen Veränderungen, Dissertation, Textband Seite 23

4.3 Magnesia

Magnesia is, chemically speaking, pure MgO and, in the technical literature, it is also often called periclase. The melting point of magnesia is at 2800°C and, for this reason, it is predominantly used in the refractory industry.

The mineral is preferably utilized in the high temperature range, e.g for steel converter lining. The majority of magnesia products is employed in the steel industry (63%) and in the cement industry (13%).⁶⁷

4.4 Magnesia Industry worldwide

Magnesite is the most important and the most commonly magnesium-containing mineral. The main field of application of dead burned magnesia or fused magnesia is the refractory industry because of the material's excellent heat resistance. Table 2 demonstrates all of the different industrial sectors in which magnesia is used.

	World Total Consumption [1000 t / Year]	Percentage [%]
Refractories (shaped & unshaped)	8.000	83,1
Agricultural (animal feed & fertilizers)	500	5,2
Environmental	550	5,7
Pulp & Paper	50	0,5
Construction (Flooring - Abrasives - Panels)	120	1,2
Heating Elements	55	0,6
Welding Fluxes	30	0,3
Ceramics	40	0,4
Magnesium Metal	200	2,1
Chemicals	80	0,8
Total	9.625	100

Table 2: Field of application of Dead Burned Magnesia (Source: Euromines)

⁶⁷ cp. Umweltbundesamt GmbH, I.c., p. 113

4.4.1 Magnesia producers within the European Union

The total number of magnesia-producing companies within the European Community is eight, as Table 3 demonstrates. Altogether, these eight producers operate fourteen mining areas and processing plants.

Producer	Country	Type	General owner
Breitenau	Austria	natural	RHI-AG
Hochfilzen	Austria	natural	RHI-AG
Radenthein	Austria	natural	RHI-AG
Styromag	Austria	natural	Steirische Magnesitindustrie GmbH
Premier Periclas	Ireland	synthetic	Irish Cem. CRH
Grecian Magnesite	Greece	natural	Portolos Group
Magnesitas de Rubian	Spain	natural	Portolos Group
Magnesitas Navarra	Spain	natural	Portolos Group
SMZ Jelsava	Slovakia	natural	Slow. Management
SlovMag AS	Slovakia	natural	Magnezit Group
Nedmag	Netherlands	synthetic	Wühlfrath Ref.

Table 3: Magnesia producers within the EU – 27 (Source: Drnek 2002)

4.4.2 Various modifications of magnesia

Magnesia occurs in three different modifications:

- **Caustic Calcined Magnesia**
- **Dead Burned Magnesia**
- **Fused Magnesia**

Caustic Calcined Magnesia – CCM

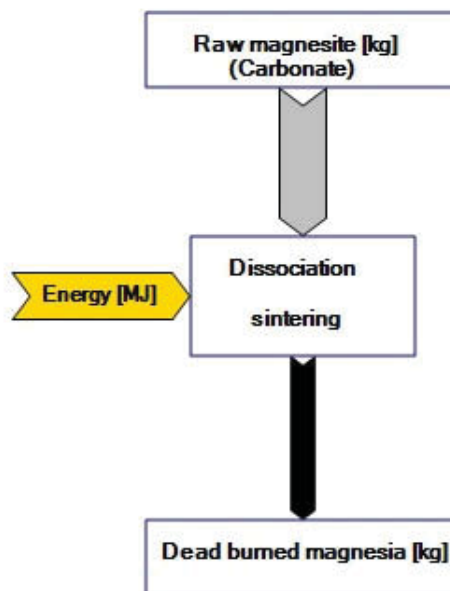
Caustic-calcined magnesia MgO (light-burned magnesia) is the outcome of a firing process (at 600-800°C). CCM is dissociated magnesite ($MgCO_3$) or calcined $Mg(OH)_2$ in which the natural crystal structure does not change during the thermal treatment.

CCM is a very porous and reactive material, which is characterized by a higher specific surface area, in contrast to dead burned magnesia or fused magnesia. Fundamentally, CCM does not have any stiffness or strength and, therefore, the mineral usually occurs in the form of powder or loose lumps.⁶⁸

⁶⁸ cp. Umweltbundesamt GmbH, I.c., p. 117

Dead Burned Magnesia – DBM

DBM (MgO) is produced through the addition of high thermal-energy to caustic calcined magnesia. It is characterized by a cubic crystal lattice with a raw density of $>3,10\text{g/cm}^3$ and crystal size ranging from 50 - 200 μm . DBM is used in the form of basic bricks and granular refractories and has the highest melting point of all common refractory oxides. Thus, it is most suitable for heat containment material, e.g. high temperature processes in the steel industry.⁶⁹ The quality of Dead Burned Magnesia (density, grain size) is vital and depends on the sintering process. Beside all of the physical parameters, the chemical composition is decisive for a successful application in the refractory. Impurities caused by, for example, boron or silicium decrease the melting point dramatically. On the other hand, DBM characteristics can be influenced through doping, e.g. with Cr, Zr.⁷⁰



Fused Magnesia – FM

Fused magnesia (MgO) is superior to dead burned magnesia with regards to stiffness, strength, abrasion resistance and chemical stability.⁷¹ FM is melted in an electric arc furnace ($>2800\text{ }^\circ\text{C}$). The properties of FM are similar to DBM, only its grain size ($>500\mu\text{m}$) and density ($>3,50\text{g/cm}^3$) are different.⁷² FM exhibits a poor resistance to heat shock, but its slag resistance is superior when compared to DBM. Due to this, FM is used for special purposes, e.g. in nuclear reactors and in refractory. China produces 95% of the world's fused magnesia.

⁶⁹ http://www.azom.com/Details.asp?ArticleID=1343#_Calcined_Magnesia

⁷⁰ cp. Umweltbundesamt GmbH, I.c., p. 117

⁷¹ http://www.azom.com/Details.asp?ArticleID=1343#_Calcined_Magnesia

⁷² cp. Umweltbundesamt GmbH, I.c., p. 117

5 Production processes for manufacturing of Magnesia

5.1 Raw materials for producing magnesia

Magnesium carbonate (MgCO_3) and magnesium chloride ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) are the key natural sources for producing dead burned magnesia. Periclase (MgO) does not occur in nature, since magnesium oxide reacts with H_2O to turn into magnesium hydrate ($\text{Mg}(\text{OH})_2$). Therefore, periclase can be recovered from magnesite ore, seawater or brines.⁷³

5.2 Production processes

Basically, there are two different types of magnesia (MgO) production:

- **natural procedure**
- **synthetic procedure**

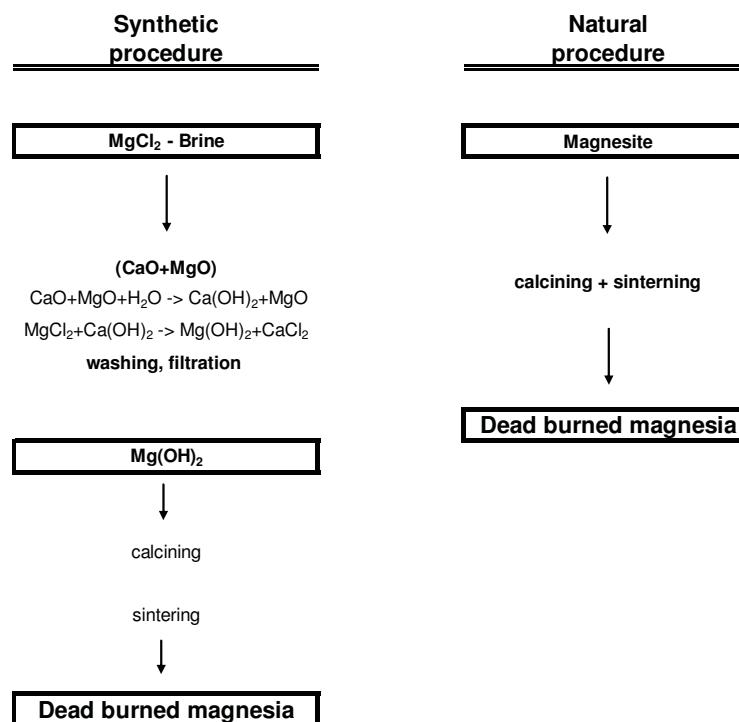


Figure 4: Main types of production processes (Source: Bundesumweltamt)

⁷³ cp. Umweltbundesamt GmbH, I.c., p. 116

5.2.1 Synthetic procedure

Seawater Magnesia

It is not possible to extract Mg from seawater directly. The synthetic procedure consists of adding calcined dolomite to seawater in order to produce magnesium hydroxide, which is then filtered and reacted with Hydrochloric acid. For clarification, the process sequence is shown below.

- I. Separating of dissolved Ca^{2+} ⁷⁴
 $\text{Ca}(\text{HCO}_3)_2 + \text{H}_2\text{SO}_4 \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + 2\text{CO}_2$

- II. chemical precipitation ⁷⁵
 $\text{MgCl}_2 + \text{Ca}(\text{OH})_2 \rightarrow \text{Mg}(\text{OH})_2 + \text{CaCl}_2$

- III. post-treatment ⁷⁶
 - a. $\text{Mg}(\text{OH})_2$ – brucite
Calcining and sintering (multi-decker passage kiln or a similar aggregate)
 $\text{Mg}(\text{OH})_2 \rightarrow \text{MgO} + \text{H}_2\text{O}$

 - b. Dissolution as bicarbonate
 $\text{Mg}(\text{OH})_2 + 2\text{H}_2\text{CO}_3 \rightarrow \text{Mg}(\text{HCO}_3)_2 + 2\text{H}_2\text{O}$
Residual Ca^{2+} could be precipitate as CaCO_3 .
Precipitates as Carbonate by “boiling“ and filtration
 $\text{Mg}(\text{HCO}_3)_2 \rightarrow \text{MgCO}_3 + \text{H}_2\text{O} + \text{CO}_2$

⁷⁴ H.Harmuth und Mitarb., Basische Feuerfeste Baustoffe, WS 2000/01

⁷⁵ H.Harmuth und Mitarbeiter, I.c.

⁷⁶ H.Harmuth und Mitarbeiter, I.c.

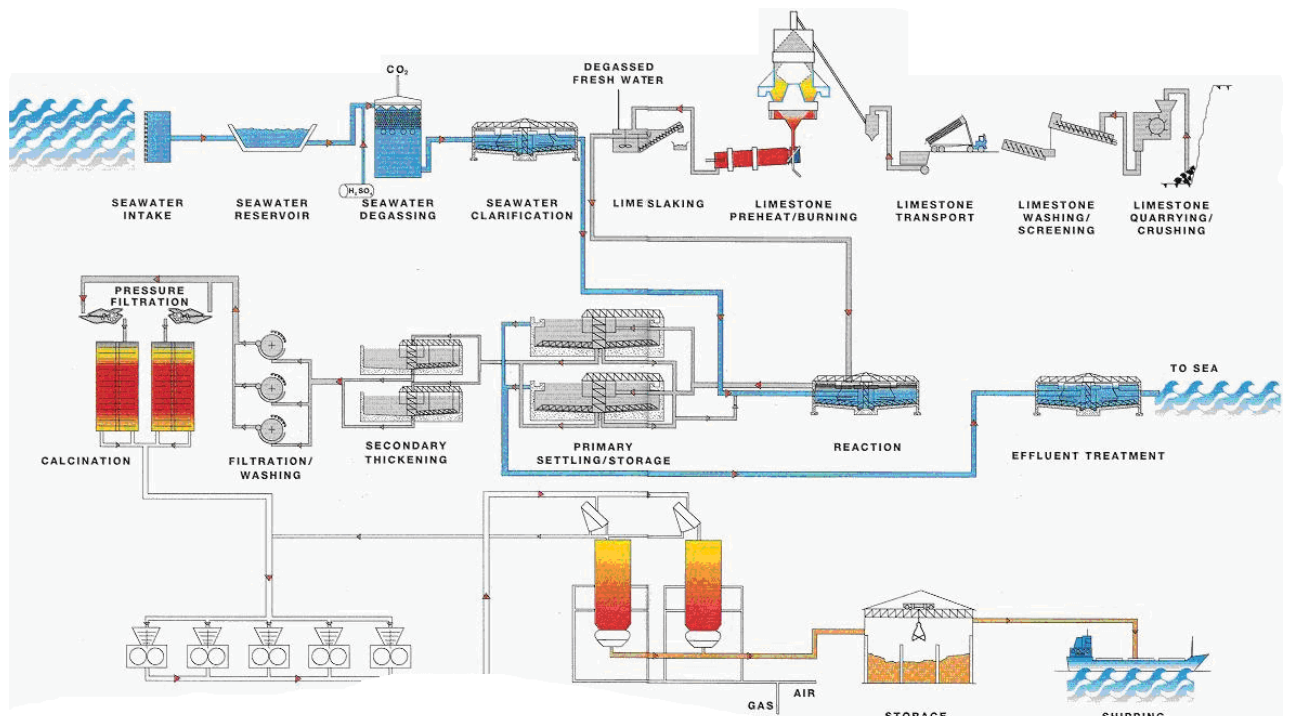


Figure 5: Flow-chart of producing seawater magnesia (Source: Premier Periclase) ⁷⁷

Brine Magnesia

Brine is, essentially, a saturated salt solution, which contains magnesium chloride, calcium chloride and water.⁷⁸ Two different types of processes are used to extract the MgO from the brine. The NEDMAG –process and AMAN-process, the latter of which will be explained in a detailed manner.

AMAN – PROCESS:

- I. Precipitation of dissolved Ca^{2+} with MgSO_4 or H_2SO_4 to $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$; filtration
- II. MgCl_2 pyrolytic cleaved in an Aman – reactor; temperature range: 400-600 °C.

$$2\text{H}_2\text{O} + \text{MgCl}_2 + \text{MgSO}_4 \rightarrow 2\text{MgO} + 2\text{HCl} + \text{H}_2\text{SO}_4$$

⁷⁷ Premier Periclase, Schematic Flow Chart, <http://www.premierpericlase.com/images/processflowsheet.gif>

⁷⁸ <http://www.magnesiumspecialties.com/students.htm#brine>

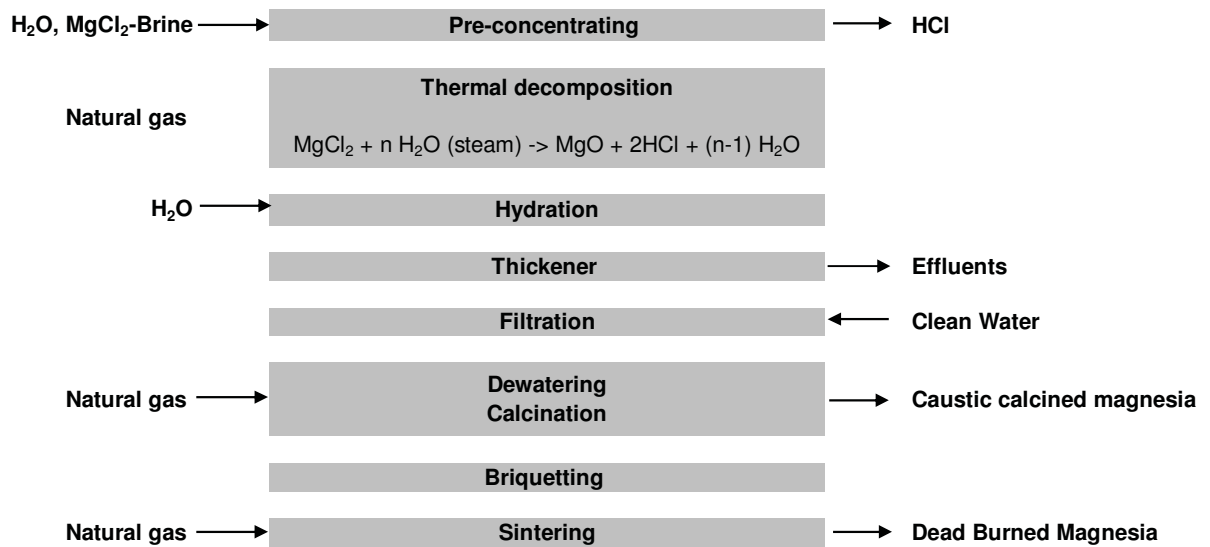
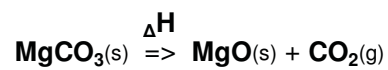


Figure 6: Flow-chart of the Aman – process (Source: Harmuth 2001)

5.2.2 Natural procedure

The natural procedure is characterized by an alkali carbonate reaction during exposure to thermal energy input. In this way, magnesia (MgO) and carbon dioxide (CO_2) are produced.

The endothermic reaction is shown below:



5.2.3 Characteristics of the decomposition of magnesite

The alkaline-earth carbonate magnesite (MgCO_3) via a burning process becomes DBM or doloma depending on the type of reactor and the difference in temperature (1600 – 1900 °C).⁷⁹ Basically, the different firing temperatures are depending on the purity of the raw material used and the desired porosity or density.

On the one hand, impurities (SiO_2 , Fe_2O_3 , Al_2O_3) affect the firing temperature as well the usability of the sinter and, on the other hand, they have a main influence on the burning processes. Therefore, raw material (mineral composition: minimum 45% MgO, maximum 1,5% CaO and 1,7% SiO_2) can only be calcined with high quality fuels (natural gas, fuel oil).⁸⁰ The dissociation process starts at 350-400 °C and ends at 500-600 °C. The sinter process starts at a temperature of more than 1000 °C. At a temperature ranging from 850 - 950 °C, the mineral is fully calcined and has no mechanical resistance.

At a firing temperature of 1800 °C⁸¹, the sinter adopts the mineralogical structure as well as the physical properties. Depending on the mineral phase content, merwinite formation ($3\text{CaO}\cdot\text{MgO}\cdot 2\text{SiO}_2$) or monticellite formation ($\text{CaO}\cdot\text{MgO}\cdot 2\text{SiO}_2$) can occur and fosterite formation ($2\text{MgO}\cdot\text{SiO}_2$) can also possibly take place (temperature range 900-1450 °C). For the technical application, the magnesite dissociation of the mineral is a significant step. It needs to be considered that the partial pressure of CO_2 reaches 1bar at 350 °C, which could lead to an unwanted disintegration of the rock.⁸²

5.2.4 Single-stage firing process

DBM is produced in one production step as a result of the single-stage firing process. The biggest benefit is the low energy consumption as opposed to using a multiple-stage firing process. However, the raw material is decisive for the sinter qualities, because no other substance (zircon oxide, chromium oxide) can be added to modify the mineral composition.⁸³

⁷⁹ L.M.Ludera (1978): Drehrohröfen zum Magnesit brennen, Gleiwitz/Polen, Zement-Kalk-Gips – Nr.12

⁸⁰ L.M.Ludera, I.c.

⁸¹ Ullmann (1960): Encyklopädie der Technischen Chemie, München-Berlin, Bd.12, S125

⁸² L.M.Ludera, I.c.

⁸³ cp. Umweltbundesamt GmbH, I.c., p. 123

5.2.5 Multiple-stage firing process

As a first step, the raw material (MgCO_3) is calcined and ground into CCM. After passing a briquetting press, CCM briquettes enter a rotary kiln or a shaft kiln and are processed into DBM. The main advantage of a multiple-stage firing process is the potential to have significant influence on the sinter properties by doping with other chemicals (zircon oxide, chromium oxide).

In the case of a huge diversity of mineral deposits, a variety of production methods are applied. The main aggregates for the production of CCM and DBM are still the rotary kiln and the shaft kiln.

5.2.6 The rotary kiln

In most instances, rotary kilns for carbonate rocks have flushed torque tubes with or without heat transfer internals. Some types of rotary kilns have a zone enlargement.

“However, this causes different transportation times resulting in irregular material passage, thus impairing the kiln’s operation. Practical experiences as well as theoretical deliberations lead to the observation that rotary kilns without constrictions or enlargements represent currently the most useful kiln construction.”⁸⁴

Generally, the burner pipe is positioned in the center of the rotary kiln’s cross-section. No collision of the flame with the material bed is possible and, therefore, good burning results are achieved.⁸⁵

The fundamental advantages of the rotary kiln are listed below:⁸⁶

- huge daily output; some thousand tons per day
- great flexibility in operation
- firing process at different temperatures possible
- range of grain size (4,0-40mm) is more applicable than grain size range for shaft kilns
- flexible transfer rate
- constantly high product quality
- quick heat dissipation after shutdown
- coating easy to remove
- easy to manage and control the firing process

⁸⁴ W.H.DUDA, Cement Data Book, International process engineering in the cement industry: 2nd Edition; p. 320

⁸⁵ W.H.DUDA, I.c., p. 338

⁸⁶ L.M.Ludera, (1987): Vergleichende Betrachtung zur Dimensionierung von Drehrohröfen für Carbonatgesteine, Polen

The fundamental disadvantages of the rotary kiln are as follows:⁸⁷

- high energy input
- increased costs for dust collection
- major place requirement and upper investment costs compared to a shaft kiln

5.2.7 The Lepol-kiln

“The intension of the Lepol kiln in 1928 was a significant development in the field of the dry production process, when considered from the viewpoint of heat economy, especially under European manufacturing conditions.”⁸⁸

“The main characteristic of this process is a short rotary kiln working in conjunction with a travelling grate; the grate itself is covered with a 15-20cm thick layer of raw material pellets or granulates, penetrated by 1000 °C hot kiln exit gases. Due to the filtering effect of the layer of granules, the dust load of the exit gases is very low; also the low temperature as well as the content of water vapour makes the exit gases ideally conditioned for electrostatic precipitation.”

⁸⁹

5.2.8 The shaft kiln

The shaft kiln is the second aggregate besides the rotary kiln, which is primarily used for industrial CCM or DBM production in Europe. Varying geometries (oval, angular or round) and a wide spectrum of fuels (fuel oil, natural gas, coal) allow a broad field of application, as demonstrated below:⁹⁰

- a. sintering of magnesite and dolomite
- b. calcining of bauxite
- c. sintering of calcined minerals in a multiple-stage firing process, e.g. magnesite, dolomite, alumina, magnesite-alumina, spinel

Operating temperatures of up to 2,200 °C, flexible temperature settings as well as a high thermal degree of efficiency are the basic features of a shaft kiln.

⁸⁷ L.M.Ludera, (1987): Vergleichende Betrachtung zur Dimensionierung von Drehrohröfen für Carbonatgesteine, Polen

⁸⁸ W.H.DUDA, I.c., p. 375

⁸⁹ W.H.DUDA, I.c., p. 375

⁹⁰ <http://www.polysius.com/Hochtemperatur-Schachtofen.427.0.html>

5.2.9 The significance of fuels for magnesia production

In magnesia production, natural gas, petrol coke and fuel oil are utilized.

Alternative fuels, like waste, biomass, cannot be made use of, as in other industries of the sector (cement industry and lime industry).

The combustion temperature of alternative fuels is not as high as for fossil fuels. Moreover alternative fuels contaminate the final product through residue as a result of combustion process. The combustion temperature has also great influence on the melting phase conditions. Therefore the usage of alternative fuels decreases the product quality in a significant way.

6 Theoretical foundations pertaining to the magnesia production

In order to follow the magnesia production process in detail, dissociation and the melting phase formation need to be understood. For that reason, this chapter demonstrates the technical and chemical basis for producing DBM.

6.1 Theoretical necessary energy input

6.1.1 Basics of the dissociation

To optimize the combustion process and, thereby, the energy input, the thermal decomposition behaviour of a single carbonate grain under certain process conditions needs to be established. *“The rate of decomposition of a piece of carbonate is determined by the following five sub-processes:⁹¹*

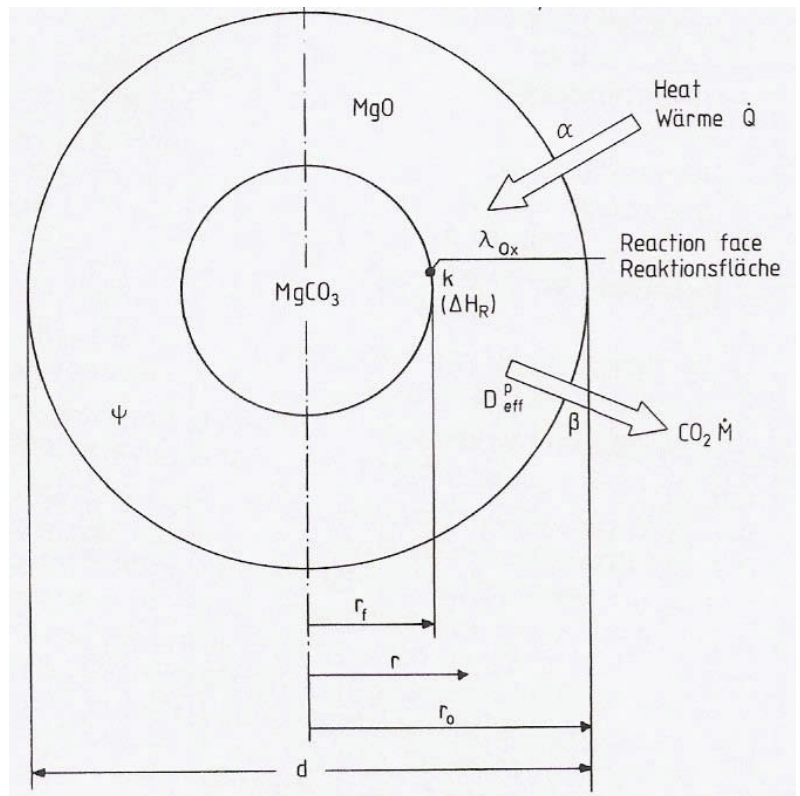
- *namely heat transfer to the material,*
- *heat conduction inside the material*
- *chemical kinetics of the decomposition reaction*
- *diffusion of the splitted CO₂ through the porous oxide layer to the surface of the material*
- *mass transfer”*

“The decomposition of magnesite is an endothermic topochemical reaction in which the conversion takes place at a moving phase layer. This mechanism is explained with reference to a partly decomposed piece of carbonate with the shape of a sphere.”⁹²

⁹¹ Eckehard Specht, Hartmut Kainer, Rudolf Jeschar (1986): Die Reaktions-, Porendiffusions- und Wärmeleitkoeffizienten verschiedener Magnesite und ihr Einfluss auf die Zersetzungszeit; Clausthal-Zellerfeld, Radex-Rundschau; Heft 4, Seite 250

⁹² Eckehard Specht, Hartmut Kainer, Rudolf Jeschar, l.c., p. 250

T_u	temperature of the calcination reaktor
T_o	surface temperature
T_f	decomposition temperature
Ψ	porosity
k	chemical reaction front
α	convection



“In the calcinations reaktor with the temperature T_u the heat is transferred by radiation and convection to the oxide layer with the surface temperature T_o . By conduction the (λ_{ox}) heat passes through the porous oxide layer with the porosity (ψ) to the reaction layer where the decomposition temperature T_f is established.”⁹³

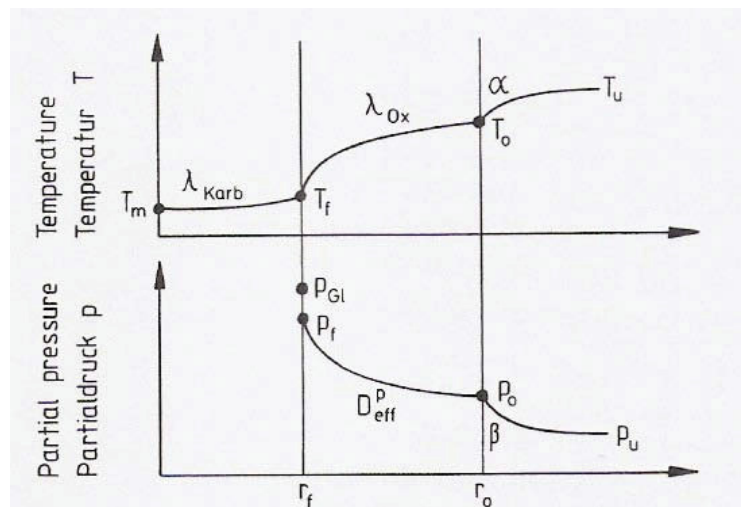


Figure 7: Decomposition of magnesite

“Sustained by the appropriate supply of heat, the chemical reaction (k) then takes place, for the driving force of which a deviation ($p_{Gl}-p_i$) from equilibrium of the CO_2 partial pressure is necessary. The released CO_2 diffuses (D_{eff}^p) through the porous oxide layer to the surface and reaches by convection (β) the ambient atmosphere with the CO_2 partial pressure (p_u).”⁹⁴

⁹³ Eckehard Specht, Hartmut Kainer, Rudolf Jeschar, I.c., p. 250

⁹⁴ Eckehard Specht, Hartmut Kainer, Rudolf Jeschar, I.c., p. 250

Basically, the physical transport processes and the chemical kinetics at the reaction front are interconnected.

“The decomposition behavior may mathematically be described by analytical solvable equations, if the following assumptions are made: ⁹⁵

- *The pieces of carbonates are to be regarded as spheres, cylinders or plates*
- *The heat supply is symmetrical, so that all processes can be treated as one-dimensional*
- *The chemical and the structural composition of the raw material is homogeneous*
- *The reaction starts uniformly on the surface, always forming a geometrically smooth decomposition front, which advances continuously into the interior of the body. Macroscopically, this assumption is certainly correct, because the edges of the individual crystals are the preferred locations where the reaction starts. This is the reason why the actual reaction surface is somewhat larger than the assumed smooth surface. The difference is incorporated in the reaction coefficient k .*
- *The heat transfer can be described by any effective heat transfer coefficient, which comprises radiation and convection*
- *The ambient state (p_u, T_u) is constant*
- *The properties as well as the heat transfer coefficient and the mass transfer coefficient are constant within the small temperature range, which has been investigated.*
- *The internal energy (stored energy) is negligible in comparison with the reaction enthalpy during the decomposition time.”*

The decomposition of magnesia is shown with different kinds of magnesite ore. **FactSage 3.2** was used to demonstrate the dissociation process and the CO₂ diffusion.

⁹⁵ Eckehard Specht, Hartmut Kainer, Rudolf Jeschar, I.c., p. 251

The basic data⁹⁶ of different kinds of magnesite (mineralogical composition) are shown in table 4.

Magnesite A

Raw Magnesite			Dead Burned Magnesia		Carbon Dioxide	
Mineral	Residue %	Mass %	Mineral	Mass %	Gas	Mass %
MgCO ₃	47,80	187,02	MgO	89,40	CO ₂	97,62
FeCO ₃	100,00	6,50	Fe ₂ O ₃	6,50	CO ₂	0,00
CaCO ₃	56,03	4,46	CaO	2,50	CO ₂	1,96
SiO ₂	100,00	0,60	SiO ₂	0,60	CO ₂	0,00
Minor Phase	100,00	1,00	Minor Phase	1,00	CO ₂	0,00
Sum	-	199,58		100,00	CO ₂	99,58

Magnesite B

Raw Magnesite			Dead Burned Magnesia		Carbon Dioxide	
Mineral	Residue %	Mass %	Mineral	Mass %	Gas	Mass %
MgCO ₃	47,80	199,99	MgO	95,60	CO ₂	104,39
Fe ₂ O ₃	100,00	0,30	Fe ₂ O ₃	0,30	CO ₂	0,00
CaCO ₃	56,03	4,46	CaO	2,50	CO ₂	1,96
SiO ₂	100,00	0,60	SiO ₂	0,60	CO ₂	0,00
Minor Phase	100,00	1,00	Minor Phase	1,00	CO ₂	0,00
Sum	-	206,35		100,00	CO ₂	106,35

Table 4: Mineralogical composition of different kinds of magnesite

Dissociation of magnesite A and the released amount of CO₂

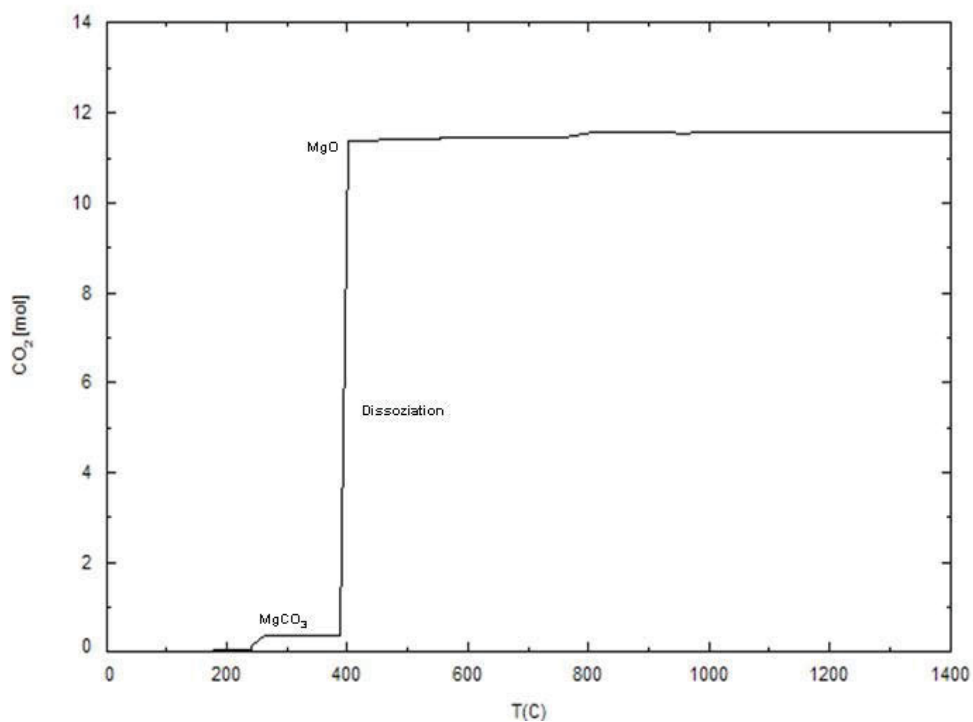
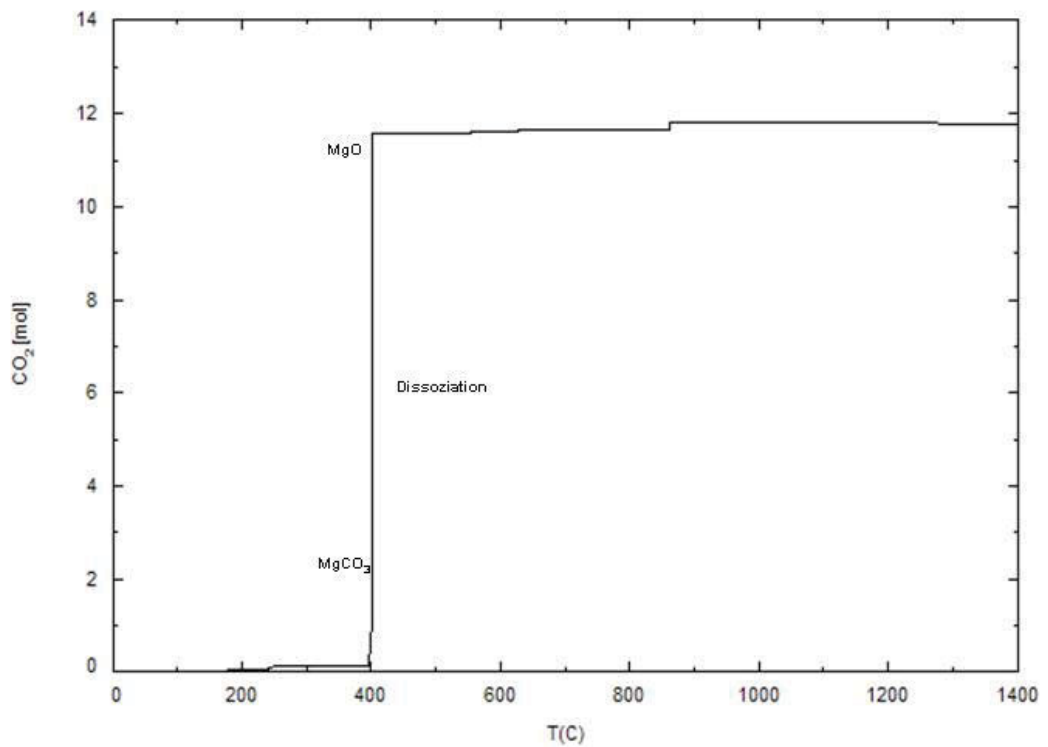


Figure 7: Dissociation of magnesite A and the released amount of CO₂

⁹⁶ Drnek T.(2002), I.c. Anhang, 04-01-Co2-bil2.xls; p. 2

Dissociation of magnesite B and the released amount of CO₂Figure 8: Dissociation of magnesite B and the released amount of CO₂

The thermo-dynamical energy input and the accrued CO₂ emissions are shown in fig.7 and fig.8. Both figures, representing magnesite A and magnesite B, were created with FactSage 3.2.

At this point, it is imperative to recognize that 50% of the raw material diffuses (CO_2), which cannot be avoided by any technical arrangements. Figure 9 demonstrates the actual results from fig.7 and fig.8 in a more visual way.

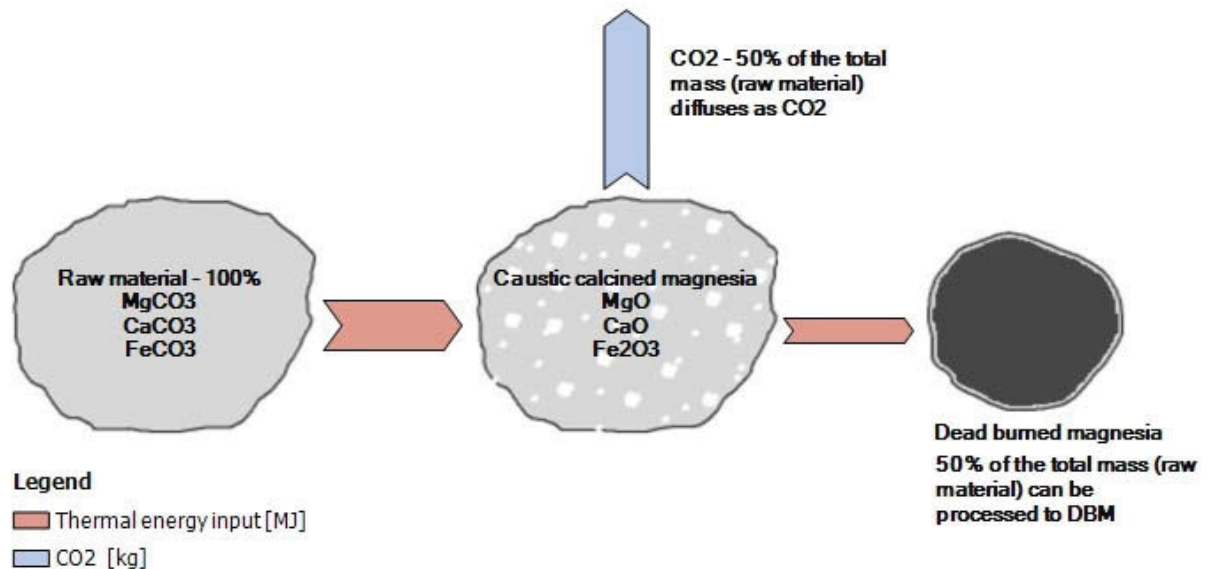


Figure 9: Weight loss (CO_2) during the firing process

The dissociation distribution of magnesite is quite similar to the dissociation of lime stone; thus, the firing process of lime stone can be compared to the firing process of magnesite.

An investigation into different types of magnesite was made in a study about “Combustion behaviour of limestone from different geological formations”⁹⁷ and an alternating behaviour during the firing process was determined. The study discovered that the geological age has no bearing on the firing behaviour. Simply put, the origin of the deposit and the different chemical compositions are responsible for this alternating behaviour during the firing process in limestone as well as magnesite.

⁹⁷ cp. Hans Lehmann, Clausthal, Josef Wuhrer, Walter Lahl, Wülfrath (1958); Das Brennverhalten von Kalksteinen aus geologischen Formationen, Mitteilung aus dem Institut für Steine und Erden der Bergakademie Clausthal und dem Forschungslaboratorium der Rheinischen Kalksteinwerke in Wülfrath

6.1.2 Basics of the sintering process

To produce dead burned magnesia, caustic calcined magnesia needs to be sintered. The firing period is a decisive control factor for product properties.⁹⁸

The geometry of every single grain (carbonate pieces) is of critical importance when one considers the energy input of the sinter process. The individual stages of the sintering process are analysed in detail and can be found in various literature [⁹⁹, ¹⁰⁰]. It has to be mentioned that numerous influencing factors during the sintering process cause a strong diffusion.¹⁰¹

The kinetics of the sintering of particles with a complex geometrical shape is dependent on the geometrical shape of the neighbouring particles.

During the sintering process of two given magnesia analysis, about 3% of the solid material cross over into the liquid phase. The porosity is decreased decisively and, hence, the dead burned magnesia obtains its typical, refractory properties.

6.1.3 Theoretical energy input for producing dead burned magnesia out of raw magnesite

To establish the theoretical energy input for the production of dead burned magnesia from raw magnesite, thermodynamical standard works have been used and an independent theoretical foundation has been established.^{102 103}

Due to the huge temperature amplitude during the production process (temperature of the raw material – sintering temperature) and the concomitance of oxides and different mineral phases, the software “FactSage” (GTT – Technologies) was used for simulation. FactSage can calculate the conditions for multiphase, multicomponent equilibria, with a wide variety of tabular and graphical output modes, while using a large range of constraints.¹⁰⁴

⁹⁸ cp. Umweltbundesamt GmbH, I.c., p. 118

⁹⁹ Hans Eckard Exner (1978): Grundlagen von Sintervorgängen, Materialkundlich-Technische Reihe 4, p. 1

¹⁰⁰ E.Geguzin (1972): Physik des Sinterns., Leiter des Lehrstuhls für Physik der Kristalle, Universität Charkow

¹⁰¹ E.Geguzin, I.c., p. 83

¹⁰² E.A.GUGGENHEIM (1946-1966): Elements of Chemical Thermodynamics (Second Edition); Professor of Chemistry, University of Reading;

¹⁰³ I. Barin ; O. Knacke ; O. Kubaschewski (1977): Thermochemical properties of inorganic substances;

¹⁰⁴ http://www.crct.polymtl.ca/factsage/fs_general.php

“Based on proper thermodynamic models for every phase, all available thermodynamic and phase equilibrium data for a system are evaluated simultaneously in order to obtain one set of model equations for the Gibbs energies of all phases as functions of temperature and composition.”¹⁰⁵ The advantage is that the required arithmetic value can be properly interpolated and extrapolated, which usually results in very accurate estimates.¹⁰⁶

To determine the theoretical energy input for producing dead burned magnesite, the process cycle was structured in

- a. drying of raw material
- b. dissociation
- c. sintering

Ad a.: Drying of the raw material

In order to determine the theoretical energy input, different magnesite types have been investigated. The mineralogical composition of the species is demonstrated below in table 5.

Mineralogical composition of the raw magnesite [%]			
Magnesite A		Magnesite B	
MgCO ₃	92,81	MgCO ₃	97,33
FeCO ₃	4,68	FeCO ₃	0,21
CaCO ₃	2,21	CaCO ₃	2,17
SiO ₂	0,30	SiO ₂	0,29
Σ	100,00	Σ	100,00

Table 5: Mineralogical composition of the two magnesite species

The raw material enters the furnace with average moisture of 4%. The energy input for the evaporation enthalpy (referring to 1 kg sinter) is shown below.

Energy input evaporation enthalpy	193,71 kJ/kg Sinter
-----------------------------------	---------------------

Table 6: Energy input for warm-up period

¹⁰⁵ <http://www.crct.polymtl.ca/fact/documentation/>

¹⁰⁶ <http://www.crct.polymtl.ca/fact/documentation/>

Ad b.: Dissociation

Due to the effect high thermal energy input has on the carbonate, oxide formations and the release of CO₂ are characteristic of the dissociation. Table 7 demonstrates the mineralogical composition (sinter composition) after a completed dissociation.

Mineralogical composition of the sinter [%]			
Magnesite A		Magnesite B	
MgO	90,30	MgO	96,55
CaO	2,52	CaO	2,52
Fe₂O₃	6,57	Fe₂O₃	0,30
SiO₂	0,61	SiO₂	0,62
Σ	100,00	Σ	100,00

Table 7: Mineralogical composition of the sinter¹⁰⁷

The energy input for this special sinter composition is shown in table 8. It should be pointed out that the occurring oxide (FeO) from magnesite A (FeCO₃) is not stable under these conditions. FeO is transformed directly into Fe₂O₃. This reaction is exothermic, which is shown with a negative algebraic sign in table 8.

Magnesite A [KJ/kg]		Magnesite B [KJ/kg]	
MgO	2579,54	MgO	2709,38
CaO	89,03	CaO	75,21
Fe₂O₃	-13,73	Fe₂O₃	-0,81
SiO₂	0,00	SiO₂	0,00
Σ	2654,84	Σ	2783,78

Table 8: Energy input for the dissociation

¹⁰⁷ FeCO₃ reacts to FeO because FeO is not stable under these conditions

Ad d.: Sintering

Fig.10 and fig.11 demonstrates the melting phase formations compared to the temperature. The temperature difference with regards to the melting phase formations are caused by the variable iron content.

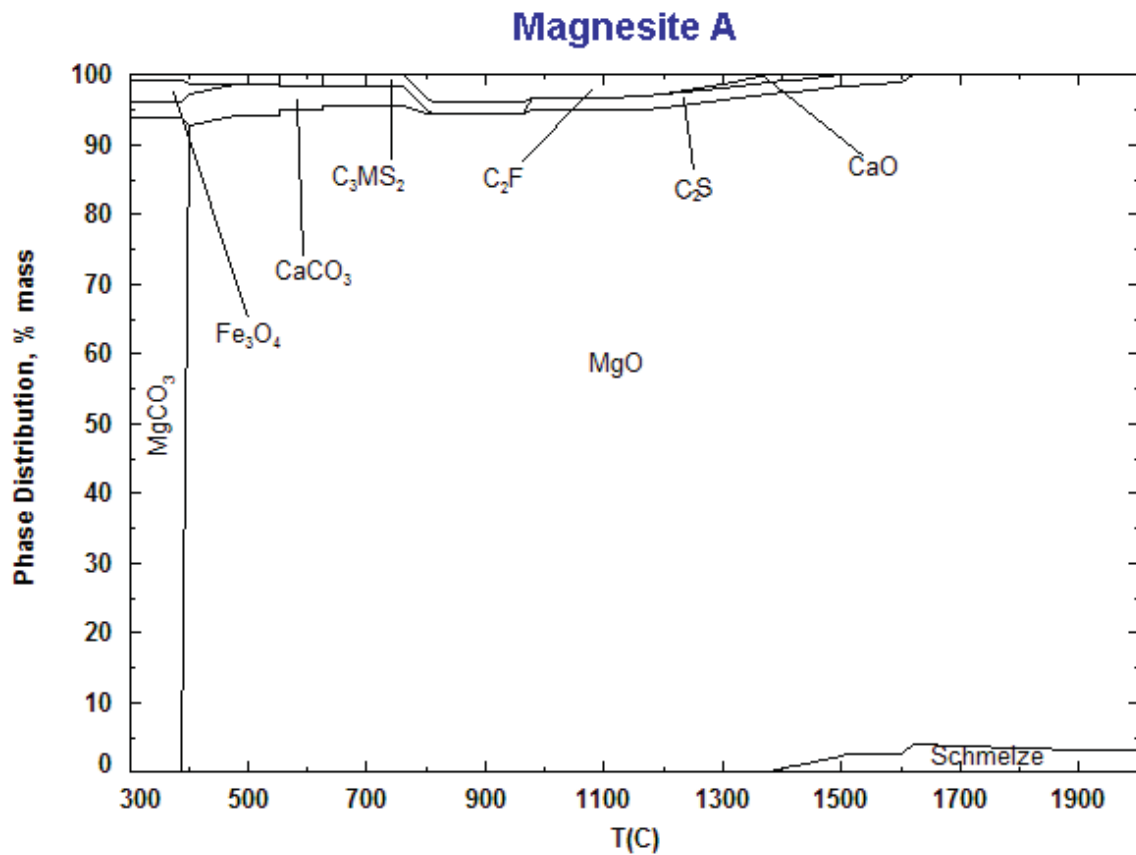


Figure 10: Melting phase formations against the temperature with regards to the sinter A

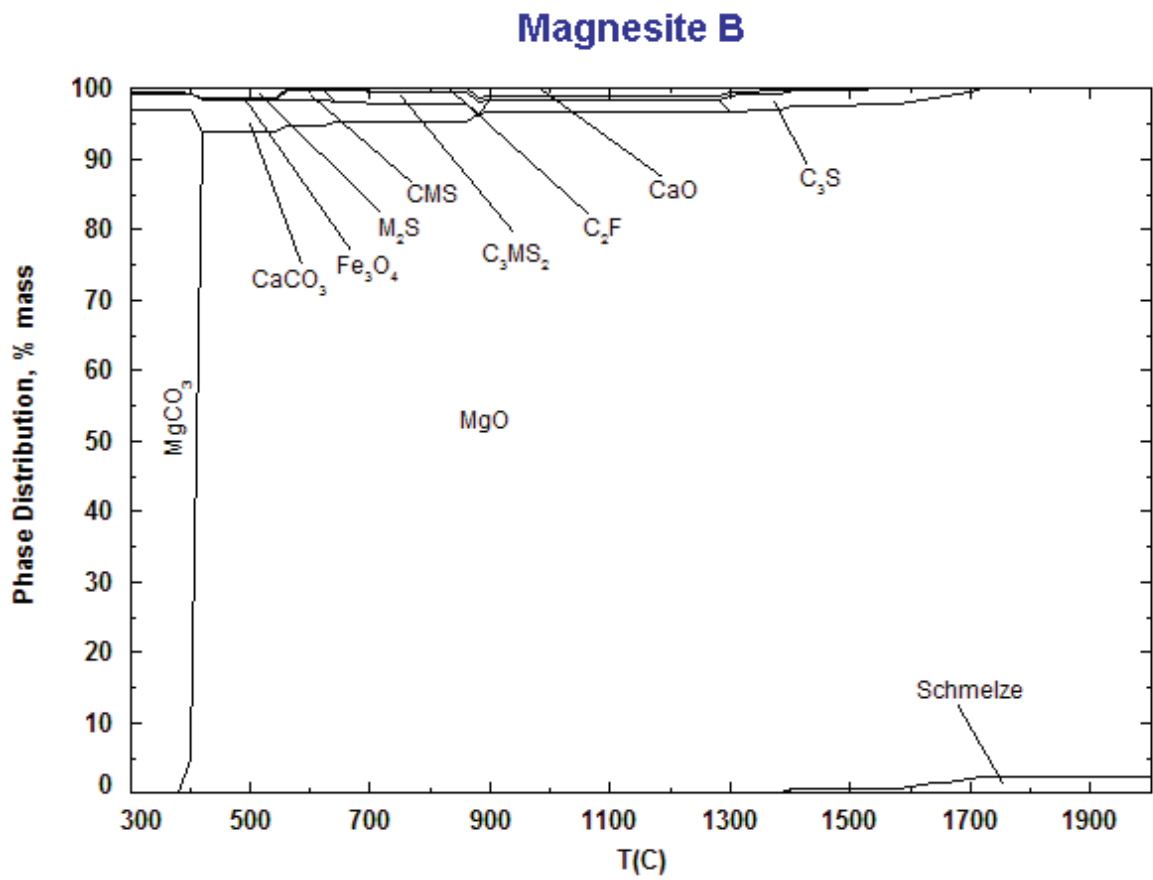


Figure 11: Melting phase formations against the temperature pertaining to the sinter B

It was assumed that the melting phase consists of C₂F¹⁰⁸ (magnesite A) and C₃MS₂¹⁰⁹ (magnesite B).

¹⁰⁸ mineral phase: C₂F stands for 2CaO·Fe₂O₃

¹⁰⁹ mineral phase: 3CaO·MgO·2SiO₂

Magnesite A	C₂F [%]	C₂F [g]
	3,13	15,298
Magnesite B	C₃MS₂ [%]	C₃MS₂ [g]
	2,37	11,417

Table 9: Amount of melting phase per kilogram sinter

The required energy for the melting phase formations are listed in table 10.

Specific melting energy		
Magnesite A	91,02	kJ/kg sinter
Magnesite B	49,81	kJ/kg sinter

Table 10: Required energy for melting phase formations

Summing up the entire theoretical energy input for the production of one kilogram of dead burned magnesia is shown in table 11.

Magnesite A		Magnesite B	
[kg Sinter]	[kg Raw material]	[kg Sinter]	[kg Raw material]
1	2,050	1	2,075
Entire theoretical energy input for 1 kg dead burned magnesia			
	kJ/kg		kJ/kg
Drying	193,71		193,71
Dissociation	2654,84		2783,78
Sintering	91,02		49,81
Σ	2939,57		3027,30

Table 11: Theoretical energy input for producing 1 kg DBM

It's clearly visible that the theoretical energy input is connected to the mineralogical composition (CaCO₃, Fe CO₃, MgCO₃) of the raw material.

6.2 Essential energy input

Due to the high temperatures needed during the production of dead burned magnesia, energy losses are unavoidable. Therefore, the energy input when producing DBM is significantly higher than the theoretical energy input.

In order to determine a representative energy amount in DBM production, a generic rotary kiln with a daily production rate of 250 t, which can be seen as representative installation for the European magnesia industry, was assumed.¹¹⁰

Combustion Tube			Cooling Tube		
Length of rotary kiln [Lc]	95,00	m	Length of rotary kiln [Lc]	30	m
Inner width [Dw]	3,00	m	Inner width [Dw]	2,8	m
Surface Temperature Range	100 - 380	°C	Surface Temperature Range	100 - 300	°C
Daily Output	250	t	Daily Output	250	t

Table 12: Specifications of the generic kiln (Source: Ludera 1978)

This generic kiln was analysed (combustion tube, cooling tube) with regards to technical unavoidable radiation losses that arise due to the high process temperatures.

Installation losses convection included	Combustion tube	1779,20	MJ / t MgO
	Cooling tube	377,61	MJ / t MgO
	Sum	2156,81	MJ / t MgO

Table 13: Radiation losses of the exemplary installation

Therefore, a higher energy demand (theoretical energy input + the technical unavoidable energy input for radiation losses) in the production of DBM is required.

	Magnesite A		Magnesite B	
Σ	5096,38	MJ/t	5184,11	MJ/t

Table 14: Theoretical energy input + the technical unavoidable energy input for radiation losses

¹¹⁰ L.M.Ludera (1978): Rotary kilns for magnesite burning, Gleiwitz, Polen ; proposed formulas for design and for thermal characteristics of magnesite kilns

Due to the high firing intensity and the low daily production rate in relation to the kiln size, the vast majority of the thermal energy losses are not reducible.

From a purely technical point of view, the product's losses as far as the thermal capacity of dust are not further reducible. Therefore, the only possible uses under debate are the energy content of flue gas and the heat emissions of the rotary kiln. All other parameters are negligibly small or, in other words, only feasible at a disproportionately high, economical and technical expense.

6.2.1 Heat emission kiln surface

The rotary kiln – as seen here in cross section – is comprised of the steel jacket, the permanent linings and the wear linings. (fig.13)

Wear linings

The wear linings have to

- resist high temperatures,
- withstand mechanical loads (bending stress, torsion, thermal gradients)
- resist the chemical influences (infiltration by sinter products)

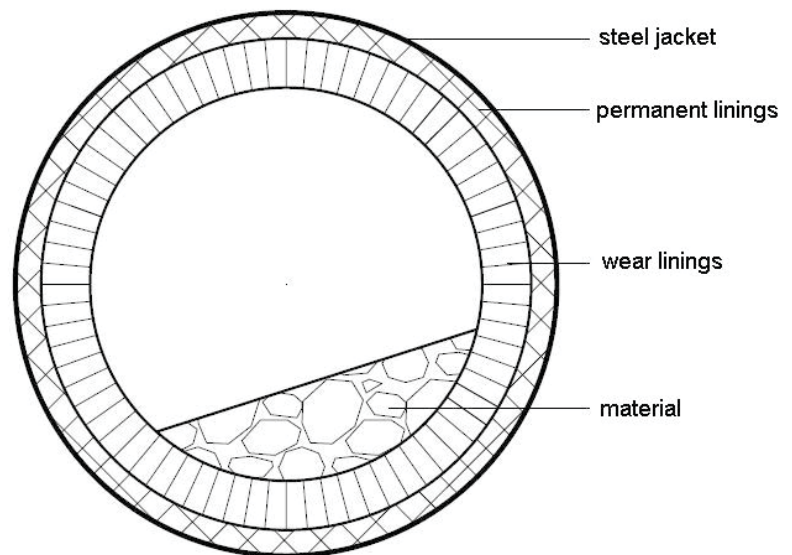


Figure 12: Cross section of a rotary kiln

Permanent linings

The permanent linings as well as the wear linings have to be able to withstand enormous mechanical strains. This means that ceramic materials with a low thermal conductivity¹¹¹ (high pore volume) cannot be used. The isolation effect is critically dependent on the pore volume of the material, which, in turn, considerably affects the mechanical strength. (The mechanical loads have to be absorbed by the mechanical strength.) It should also be mentioned that from a technical viewpoint no substitution of the ceramic material is possible due to the high temperatures (>1700°C).

¹¹¹ thermal conductivity [W/mK]

Steel jacket

Once again owing to the very high temperatures, an isolation of the steel jacket to reduce the radiation losses has to be ruled out, since the steel jacket's breaking point could possibly result in technical malfunction. As such, this is a technically necessary heat loss without the potential of reduction.

In summary, it can be stated that from a technical point of view and for the reasons mentioned above, currently no additional reduction potential exists with regards to the "heat emission kiln surface" (wear linings, permanent linings, and steel jacket).

6.2.2 Fuel Mix

From today's point of view, no substitution of fossil fuels in the production of dead burned magnesia is possible. On the one hand, alternative fuels contaminate the final product through residue as a result of the combustion process and, on the other hand, the combustion temperature of alternative fuels is not as high as for fossil fuels. This difficulty is compounded by the fact that natural gas is simply not available in some EU countries. From the technical point of view, the European lime industry is comparable with the magnesia industry pertaining to the aggregates used and the production process in general.

Moreover the European lime industry¹¹² is confronted with the same problem because the production process causes a similar amount of CO₂ emissions, which cannot be avoided by the implementation of any technical measures. Moreover, impurities (caused by the residue of alternative fuels) decrease the product quality in a significant way and, therefore, the fuel mix is limited to a small number of fuels.

¹¹² European Lime Association - EuLA (2009): Developing a Benchmark for the Lime Sector, Brussels

Fuel mix for the European lime industry

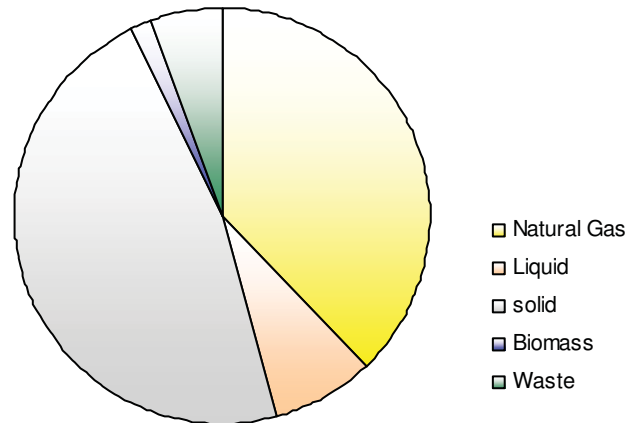


Figure 13: Average generic fuel mix /European lime industry (Source: EuLA 2009)

EuLA - Fuel Mix	Average European fuel mix in 2007-2008 (EuLA)
Natural Gas	37.67%
Liquid	8.14%
Solid	47.06%
Waste fuels	5.55%
Biomass	1.60%

Table 15: Average fuel mix; European lime industry 2007 – 2008 (Source: EuLA 2009)

Due to the higher process temperatures in the production of dead burned magnesia the thermal energy input is higher than the thermal energy input for lime based products. Furthermore, impurities (caused by residues of alternative fuels) decrease the sinter quality dramatically. On this account, the use of alternative fuels and the use of biomass have to be substituted by gas for a representative fuel mix of the European magnesia industry.

The European lime industry, compared to the European magnesia industry, is comparatively big and therefore a sufficient amount of production data is available. Furthermore, the production processes as well as the production aggregates are very similar to the magnesia industry. Out of the production data of the European lime industry, a generic fuel mix for the European magnesia industry can be derived, whereby biogenic fuels are excluded as reasons named above.

Based on the average fuel mix used in the European lime industry (2007 – 2008), a generic fuel mix for the European magnesia industry is pictured in fig. 15.

Generic fuel mix for the European magnesia industry

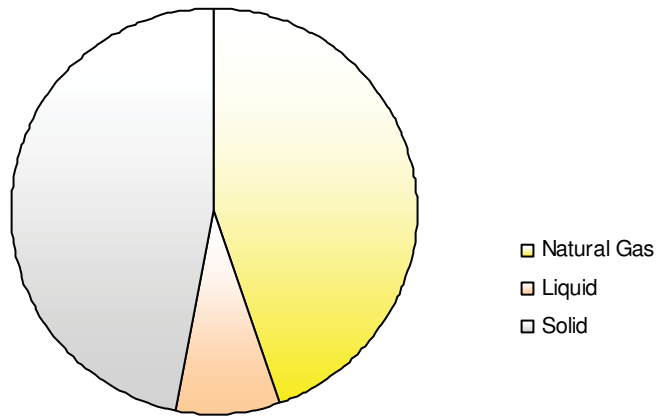


Figure 14: Generic fuel mix / European magnesia industry

Generic fuel mix for the European magnesite industry	Specific fuel mix
Natural Gas	44,80
Fuel Oil	8,14
Petroleum Coke	47,06

Table 16: Specific CO₂ emission factor / generic fuel mix for the European magnesia industry

6.2.3 Energy content of flue gas

With the state-of-the-art equipment in flue gas cleaning systems (bag filter, electrostatic precipitator; 180 °C), the exhaust gas temperature has to be significantly higher than the dew point of the exhaust gas.

The example below deals with the energy content of the flue, which implies the process related CO₂ emissions as well as the combustion products with regards to the generic fuel mix. For the calculation, the energy content from cooling the flue gas from 180 °C to 20 °C was determined.

Real combustion reaction $\lambda=1,1$					
	CO ₂	H ₂ O	N ₂	O ₂	Unit
Flue gas fuel mix	10,40	10,21	64,14	1,55	kmol / t Mgo
Process related CO ₂	23,86	0,00	0,00	0,00	kmol / t Mgo
Σ	34,25	10,21	64,14	1,55	kmol / t Mgo
Energy content	213912,38	503171,25	290057,23	7182,42	kJ/t MgO

Energy content of the flue gas	1014,32	MJ/t MgO
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Flue gas volume				
CO ₂	H ₂ O	N ₂	O ₂	Unit
767,78	228,82	1437,68	34,74	m ³ /t MgO
Σ			2469,03	m ³ /t MgO

Table 17: Flue gas volume and energy content pertaining to 1 metric ton MgO (m³ are mentioned as standard cubic meters – SCM)

Due to the prevailing pressure differences inside the furnace, false air is sucked into the system and cannot totally be avoided even by the most types of sealings. In order to determine a practically orientated gas volume, a O₂ content in the flue gas of 10% was hypothesised.

False air: O ₂ -content in the flue gas 10%					
Flue gas volume false air included	4399,35	m ³			
False air volume	1930,33	m ³			
N ₂	1524,96	m ³			
O ₂	405,37	m ³			
	CO ₂	H ₂ O	N ₂	O ₂	Unit
Σ	10,40	10,21	64,14	1,55	kmol / t MgO
Process related CO ₂	23,86	0,00	0,00	0,00	kmol / t MgO
False air volume	0,00	0,00	68,04	18,09	kmol / t MgO
Σ	34,25	10,21	132,18	19,64	kmol / t MgO
Energy content	213912,38	503171,25	597723,00	90985,34	kJ/t MgO

Energy content of the flue gas	1405,79	MJ/t MgO
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Flue gas volume				
CO ₂	H ₂ O	N ₂	O ₂	Unit
767,78	228,82	2962,64	440,11	m ³ /t MgO
Σ			4399,35	m ³ /t MgO

Table 18: Flue gas volume and energy content with false air pertaining to 1 metric ton MgO (m³ are mentioned as standard cubic meters – SCM)

All other losses, energy content of the product, energy content dust, are not respected (shall be below 1%).

6.3 Analysis and evaluation

The production process of DBM is a more energy-intensive, highly industrial process due to the

- high firing temperatures,
- the low daily production rate in comparison to the plant dimension,
- and the mineral composition of the raw material

in comparison to the cement industry or the lime sector. To determine a realistic energy demand and to demonstrate the occurring CO₂ emissions that would result from a realistic fuel mix in the production of DBM, the technical necessary energy losses (radiation, flue gas) were calculated.

The essential energy input for producing 1 metric ton of DBM is demonstrated below in table 19.

	Magnesite A	Magnesite B	Unit
Drying of raw material	193,71	193,71	[MJ / t Sinter]
Dissociation	2654,84	2783,78	[MJ / t Sinter]
Sintering	91,02	49,81	[MJ / t Sinter]
Essential energy input Generic installation	2156,81	2156,81	[MJ / t Sinter]
Energy content flue gas (based on adopted fuel mix)	1405,79	1405,79	[MJ / t Sinter]
Sum	6502,17	6589,90	[MJ / t Sinter]
Average of Magnesite A & B	6546,04	[MJ / t Sinter]	

Table 19: Essential energy input for producing 1ton of DBM

The adopted generic fuel mix for the European magnesia industry (fig.14), which is based on the average fuel mix used in the European lime industry (2007 – 2008), is listed below in table 20.

Generic fuel mix for the European magnesite industry	Specific fuel mix	Emission factor ¹⁾	Equivalent emission factor (t _{CO2} /TJ)
		(t _{CO2} /TJ)	
Natural Gas	44,80	55,4	81,93
Fuel Oil	8,14	78,0	
Petroleum Coke	47,06	104,0	

¹⁾ Bundesgesetzblatt Rep. Austria, 2007

Table 20: Generic fuel mix for the European magnesia industry

For determining the whole amount of CO₂ emissions which are emitted during the production of 1 ton sinter, the origin of the CO₂ emissions can be subdivided into two different sectors.

- **Process related emissions:** resulting from the drying, dissociation (Carbonate – Oxide) and forming of melting phases. Process related emissions cannot be reduced by any technical means.
- **Essential energy input:** represents the technical necessary energy input for the production of dead burned magnesia. For the calculation, the fuel mix and the emission factors from table 20 was used.

The total amount of CO₂ emission is calculated by the essential energy input (table 19) multiplied by the equivalent emission factor (fuel mix - table 20) plus the process related CO₂ emissions (dissociation).

	Magnesite A	Magnesite B	Unit
Process related CO ₂ emissions	1,050	1,075	[tCO ₂ / t Sinter]
Fuel mix related CO ₂ emissions	0,533	0,540	[tCO ₂ / t Sinter]
Sum	1,583	1,615	[tCO ₂ / t Sinter]

	Average of Magnesite A & B	
Process related CO ₂ emissions	1,063	[tCO ₂ / t Sinter]
Fuel mix related CO ₂ emissions	0,536	[tCO ₂ / t Sinter]
Sum	1,599	[tCO ₂ / t Sinter]

Table 21: Amount of CO₂ emissions per ton MgO

6.4 Specific CO₂ emissions

The specific carbon balances were determined based on four different examples, which were all compared with one another.

First example is the generic kiln, which can be seen as representative for the DBM production. The necessary energy input is based on the adopted fuel mix (fig. 14).

The second one represents the average CO₂ emissions of all European magnesite producers (Ø EU-27) and the third example is an operation representing a synthetic DBM production located in an OECD country.

The fourth operation is an estimation of Chinese equipment. The largest amount of CO₂ is generated by the Chinese production of DBM. As fuel, they use black coal, which causes an enormous amount of environmentally problematic emissions.

No process control or closed loops as well as filter systems are installed. Therefore the required energy input was estimated to 150% in comparison to western technology.¹¹³

¹¹³ Drnek, Maier, I.c.

Specific CO ₂ emissions [t CO ₂ /t MgO]	Generic kiln	Ø EU - 27	OECD	Chinese equipment estimation of an operation
Operation	Natural	Natural	Synthetic	Natural
Raw material	Magnesite rock	Magnesite rock	Brine	Magnesite rock
Kiln typ	Rotary kiln	-	Shaft kiln	Shaft kiln
Fuel	Generic fuel mix	Fuel Mix	Natural Gas	Coal
Dissociation Mg/CaCO₃ - Mg/CaO + CO₂ [tCO₂/tMgO]				
Magnesite	1,0625	1,093	-	1,014
Dolomite	-	-	1,114	-
Combustion [tCO₂/tMgO]				
Direct Calcination	0,5363	0,704	-	1,499
Dolomite Calcination	-	-	0,244	-
Caustic magnesia Calcination	-	-	0,429	-
Sintering	-	-	0,140	-
Sub-total	0,5363	0,704	0,813	1,499
Sum	1,599	1,797	1,927	2,513

Table 22: Comparison of the carbon dioxide balances pertaining to the different technologies and plants

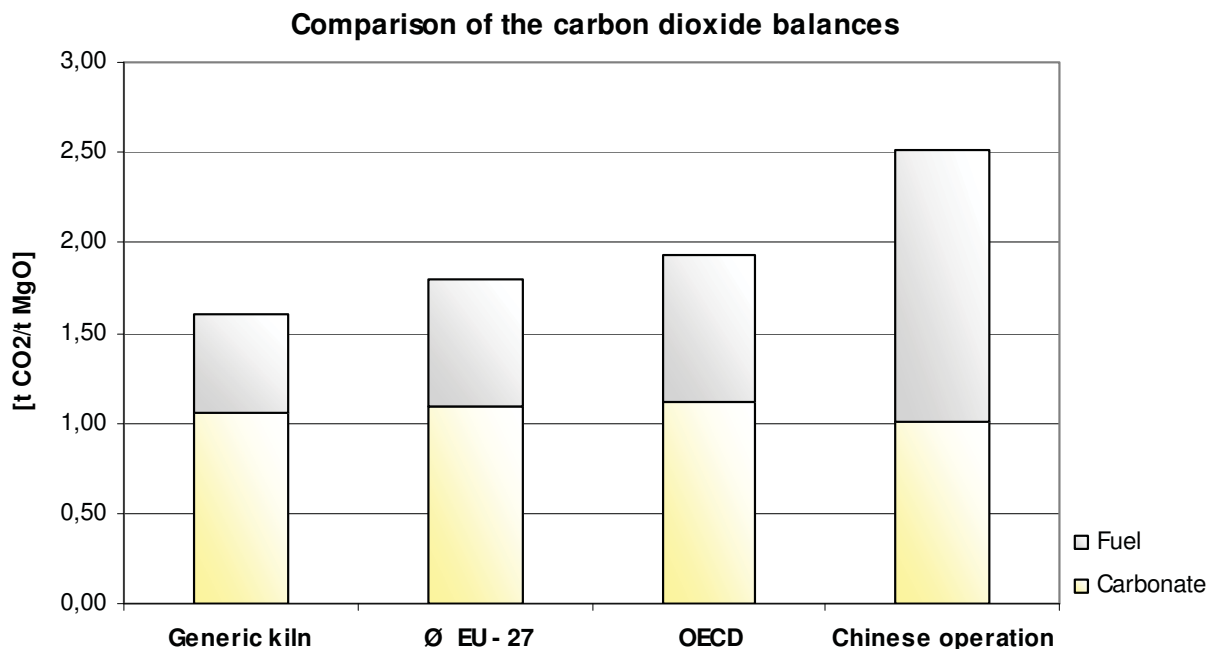


Figure 15: Comparison of the carbon dioxide balances pertaining to the different plants 15: Comparison of the carbon dioxide balances pertaining to the different plants

Fig.15 demonstrates the comparison between the different technologies and plants. The single stage firing process (generic kiln) for the production of dead burned magnesia with an adopted generic fuel mix and applying the western technology causes the lowest CO₂ emissions, followed by the average value of the EU-27 magnesia producers.

The higher CO₂ emissions of the synthetic DBM production can be explained by the careful production process compared to the single stage firing process.

Due to the firing with black coal and the deficiency of kinds of process control, Chinese operations generate the largest amount of CO₂ emissions.¹¹⁴

¹¹⁴ Drnek, Maier, I.c.

7 Conclusion and interpretation of the results

7.1 Conclusion regarding to the legal framework

The European magnesia industry is rather small compared to other energy-intensive industries (cement, steel, pulp and paper), which results in a smaller number of producers. In the course of a global climate-change policy and the resultant EU-ETS directive within the European community, the great majority of all emission allowances is allocated based on benchmarks.

As already mentioned, the small number of producers absolutely has to be taken into account when defining benchmarks. ECOFYS developed 11 allocation principles (described in chapter 3), which are fundamentally important for the definition of product-specific benchmarks.

It has to further be pointed out that the allocation principles of the ECOFYS cannot be applied to the European magnesia industry, which is already judged to be a carbon leakage risk. The reason for this is the small number of installations (statistical basic set) within the European Union and, therefore, the confidentiality of the data would be infringed upon.

For the reasons mentioned above, benchmarks need to be based and defined on an independent, theoretical foundation. This implies a precise analysis of the production process (theoretical energy input).

This is a feasible and equitable way for the definition of a benchmark for the European magnesia industry.

7.2 Conclusion regarding to independent theoretical foundations

A definition of a benchmark for the ETS for the European magnesia industry is a challenging task, because of the limited number of installations, statistical methods cannot be used.

Furthermore, because of the high temperature process for the production of dead burned magnesia, the essential energy input is significantly higher than the theoretical energy input. The major significance of the actual energy demand can be explained by the fact that high firing temperatures are necessary for the dissociation and the sintering process.

Moreover the energy demand is also influenced by the mineralogical composition and impurities.

Beside that, energy losses to a certain level are unavoidable because of the technical limits of materials and construction (surface temperature of the kiln, diluting air, isolation potential of the kilns, energy content of the flue gas).

Modern kilns are lined with high efficient insulation and refractory materials and are optimised in construction.

Based on a generic kiln (which can be seen as a representative installation for the European magnesia industry) and an adopted generic fuel mix, the resulting CO₂ emissions are determined. Further on specific carbon balances of different technologies and plants (generic kiln, average EU-27, operation representing a synthetic DBM production, operation based on an estimation of Chinese equipment) are calculated and compared with each another. Thereby high differences due to the fuel based CO₂ emissions are reflected.

This diploma thesis describes an independent, theoretical and scientific foundation for the definition of benchmarks with regards to the European magnesia industry.

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- [96] Drnek T.(2002), I.c. Anhang, 04-01-Co2-bil2.xls; p. 2
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[107] FeCO₃ reacts to FeO because FeO is not stable under these conditions

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