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MASTER THESIS

Title:

IMPORTANT TECHNOLOGICAL AND ECONOMIC ASPECTS FOR A NEW WAELZ SLAG RECYCLING CONCEPT

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This thesis presents the most important parameters for the successful recycling of slag that accumulates in the Waelz process when reprocessing steel mill dust in the Waelz kiln. In the first part, calculations such as a mass and energy balance for experiments using the top blown rotary converter at the University of Leoben are performed. These results represent the input data for the actual trials that use different initial situations for the Waelz slag recycling concept. The main objective in the process is the regaining of the value component Zn in its oxidic state. Since the slag also contains major amounts of Fe, achieving an iron alloy which shows a decent impurity grade in order to be sold to the iron and steel industry displays another goal. Therefore, the quality of the product as well as of different other factors has to be guaranteed on a constant basis.

In addition to the technological and experimental part, the economic calculation of the project's feasibility constitutes the thesis' second important aim. Here, the obtained data from the preceding step display the input information for further assumptions. The most important cost drivers for a possible realization are divided into capital expenditure, operational expenditure as well as the earnings from the achieved products and are subsequently further broken down. In total this calculation is performed for three different scenarios. The realistic case bases upon data that provide input information as close to reality as possible. Since the presented recycling method for Waelz slag depicts a totally new concept that has never been performed before, there is a given uncertainty. However, by comparing the parameters with related projects, these data approach realistic conditions. Additionally to this case, both a best and a worst case scenario are presented too. For these, some assumptions have to be made, hence showing a possible yet not entirely realistic situation. Their aim is to show the influence of the different input parameters as well as the project's broad horizon.

At the end, technological and economic numbers represent the result. By comparing the different costs with the probable earnings, the financial profitability is presented. Here, a discounted cash flow model is used in order to provide information from all over the processes' life time and to obtain a number that expresses its net present value. This NPV constitutes the core for a financing decision and consequently for the realization of the presented project.

Leoben, September 2014

Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Stephan Steinacker

Leoben, September 2014

Kurzfassung

Im Rahmen dieser Diplomarbeit werden einerseits die essentiellen technologischen und anderseits die wichtigsten wirtschaftlichen Aspekte eines neuen Recycling-Konzepts von Wälzschlacke, welches an der Montanuniversität Leoben entwickelt wird, präsentiert. Heutzutage erfolgt fast ausschließlich eine Deponierung der beim Wiederverwerten von Stahlwerksstäuben entstehenden Schlacke, was mit beträchtlichen Kosten verbunden ist. Mit der neuen Methode, die einen „Top Blown Rotary Converter“ als Reduktionsaggregat für die Einsatzstoffe verwendet, kann dieses Problem jedoch gelöst werden, wobei bei sämtlichen Aspekten Qualitätsmerkmale eine wesentliche Rolle spielen.

Der erste Teil der Arbeit setzt sich mit den physikalisch-chemischen Berechnungen auseinander, welche in weiterer Folge die Ausgangsparameter für die eigentlichen Experimente auf Labormaßstab darstellen. Weiterführend dazu erfolgt im zweiten Abschnitt die Ermittlung und Erläuterung verschiedener wirtschaftlicher Aspekte für eine mögliche Projektumsetzung. Aus diesem Grund findet die Berechnung von Finanzkennzahlen wie dem Investitionsaufwand, dem Betriebsaufwand und dem aus den Produktverkäufen entstehenden Gewinn statt. Dies geschieht in erster Linie für einen realen Fall, bei dem sämtliche Einsatzfaktoren an bereits existierende Industrieprojekte angelehnt sind. In weiterer Folge werden diese Berechnungen auch für ein bestmögliches sowie ein negativ angenommenes Szenario durchgeführt. Das primäre Ziel dieser Diplomarbeit stellt somit die Bereitstellung von Rentabilitätsdaten und in weiterer Folge die faktenbasierte Grundlage für eine Investitionsentscheidung dar.

Abstract

This diploma thesis presents the most important technological as well as economic aspects of a new recycling concept for Waelz slag that is being developed at the University of Leoben. Nowadays, a vast majority of the slag accumulating from recycling steel mill dust in the Waelz process is sent to landfill which generates costs. However, a new method using a top blown rotary converter as reaction vessel provides an interesting solution to the problem. Throughout the project different quality aspects play an important role as well.

In the first part of this work the required physico-chemical calculations are performed which consequently represent the input parameters for the actual experiments on laboratory scale. The other half deals with different economic aspects regarding the realization of this process. Therefore, financial values such as the capital expenditure, the operational expenditure and the earnings from the products are calculated and interpreted. This action is performed for a realistic case where the input factors show close reference to comparable industrial processes, whereas a best and a worst case scenario highlight different opportunities of the project. Accordingly, providing profitability information for a possible realization and hence for an investment decision represents this thesis' main aim.

Acknowledgement

This diploma thesis was written at the “CD-Labor für Optimierung und Biomasseeinsatz beim Recycling von Schwermetallen” at the University of Leoben. All included information concerns the company Befesa, a specialist in recycling steel mill dust.

I want to give special thanks to Priv.-Doz. Dipl.-Ing. Dr. mont Jürgen Antrekowitsch for offering the opportunity of composing this thesis at his laboratory. In my eyes economy plays an essential role in an engineer’s life for which reason my main concern was to integrate as many economic aspects as possible when looking for a topic. At Dr. Antrekowitsch’s chair I was given the chance to add these factors to an overall technological issue. As a result, half of the thesis deals with physico-chemical calculations and experiments, whereas the other part presents a broad variety of financial aspects.

Special thanks also go to Dipl.-Ing. Dr. mont. Stefan Steinlechner for constantly supervising the economic part of this work. As it represents a very difficult task to obtain realistic investment data such as raw material or selling prices with ordinary means, Dr. Steinlechner always offered his help concerning reference values from comparable projects in the metallurgical sector.

I further want to thank Dipl.-Ing. Christoph Pichler for his commitment regarding the technological part of this thesis. The previously performed calculations such as the mass and energy balance were carried out with his constant help. In the next step Dipl.-Ing. Pichler played an essential role during the realization of the experiments at the top blown rotary converter at the University of Leoben.

Very special thanks also belong to my mother Mag. Irmgard Steinacker. Due to her constant support and commitment she offered excellent conditions for my studies all through the years. In the same way, I want to thank my brother Mr. Thomas Steinacker for his help no matter what throughout this time. At this point I would also like to emphasize the fantastic time I had with my flat mates while studying in Leoben. Furthermore, big thanks go to Miss Bernadette Poosch for increasing my motivation at the thesis’ final stage and all the family members and friends that have been there and supported me throughout my student life.

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1 Introduction

At the moment the steel industry is growing rapidly on a global basis. As a result, the amount of by-products also increases which leads to the rising need of landfilling sites on the one hand and to new recycling concepts on the other. The presented thesis deals with the accumulating steel mill dust rich in zinc from electric steel plants. Until now these materials have in most cases been treated in Waelz kilns in order to regain the value component Zn. In this process the zinc is reduced in a rotary furnace by using a reducing agent such as coke breeze. The metal evaporates and is then reoxidized in the gaseous phase. Hence, the ZnO can be obtained from the filter in the exhaust gas system at the feeding end, whereas most of the other compounds leave the furnace on the other side.

As a product of this recycling process, the so called Waelz slag is continuously produced. It mainly consists of iron oxides, zinc oxide and slag formers like CaO and SiO_2, however, a significant amount of so called problematic substances such as potassium and chlorine are present within this product as well. Therefore, an adequate use in the construction industry is not possible which means the duty of landfilling and its combined costs. Since approximately 10 % of the value component zinc is still included within the slag, the question for a new reclaiming process arises. From a different point of view the amount of iron contained in the product also displays an interesting component that is worthy of reprocessing.

The University of Leoben is currently working on a concept that introduces a recycling concept for the accumulating slag from the Waelz kiln. This thesis' main aim is to introduce important aspects – of technological as of economic nature – to this new method. First, experiments are performed in order to demonstrate the physico-chemical practicability and to determine the best possible process parameters. In the second part the actual financial feasibility is investigated in detail. Accordingly, the input parameters from the experimental results are related with comparable projects from the metallurgical industry in order to gain comprehension of the different data. Economic values such as the capital expenditure, the operational expenditure and the earnings are presented and calculated for three different cases. The realistic case represents the reference point for financing aspects, whereas a best and a worst case scenario show the broad horizon of such a project. By considering the described parameters as well as more technological and economic data, an Excel file with all necessary information is generated. This program gives the most important information with the opportunity of easily altering input parameters. It furthermore constitutes the main factor regarding financing decisions for the realization of the new recycling concept for Waelz slag.

2 Theoretical Background

This chapter provides the most important details regarding current data from the steel industry in general on the one hand and on the other presents the different types of steel mill dust. Another part deals with the classification methods for these components such as the scanning electron microscopy or the hot stage microscope.

2.1 World Steel Production

In 2013 the world crude steel production reached 1,607 Mt which represents a growth of around 3.5 % compared to the year before. The main part came from Asia, where 1,080.9 Mt symbolised a market share of 67.3 %. China itself supplied 48.5 % and still occupies the position as clear market leader. In contrast to an increase of 6 % in the production numbers in Asian countries, the European Union showed a slight decrease of -1.8 %, producing 165.6 Mt overall which represents about 10.3 % of the world production. Figure 1 shows an overview of the production development, placing an emphasis on the strong progression in China.[1][2]

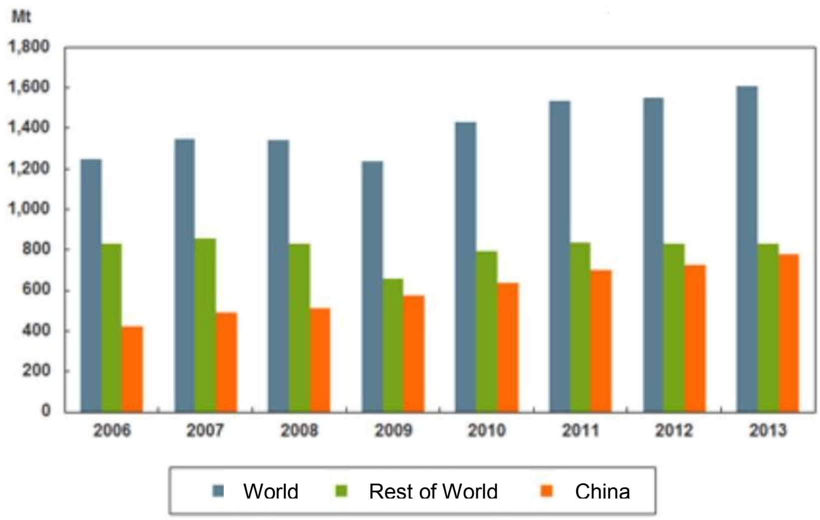

Figure 1: World Crude Steel Production[1]

Around 75 % of the total amount of steel is being produced from pig iron, making this the most important material for further processing. The combination of the blast furnace (BF) and the basic oxygen furnace (BOF) plays the most significant role with a share of 66 %, followed by the direct reduction (RD) and the electric arc furnace (EAF) with 6 % and the open hearth furnace providing 3 %. The other 25 % is being produced secondarily by melting steel in electric arc furnaces (EAF).[3][4]

In order to transform pig iron and additional recycling material into crude steel, numerous processes have to be performed depending on the required quality. At the moment investigation work is carried out to develop recycling strategies for the residues that accumulate during these steps in order to achieve a so called zero waste process. Despite these efforts as well as rising environmental requirements and stricter laws, a significant part of the by-products is still stored or deposited offering a new opportunity for new technologies.[5]

2.2 Residuals from the Iron and Steel Industry

The residuals that accumulate during the crude steel production process are currently either deposited or being further processed to obtain a secondary raw material that can be used itself or as well be sold. The essential residual materials can be divided in two categories. The first one represents slags that originate from the blast furnace or the steel making process during steps like oxidization of the pig iron, desulphurization or secondary metallurgical processes. The other group consists of filter dust and sludges that appear in the off gas treatment. Austrian steel producer Marienhütte GmbH for example states a stable value of around 18 kg dust collected per ton of steel produced[6], whereas just in the country of Germany around 3 million tons of galvanized thin sheet scrap accumulate each year.[7] Figure 2 shows the most important by-products of the steel production process, for the primary route as well as for the secondary one.[5][8]

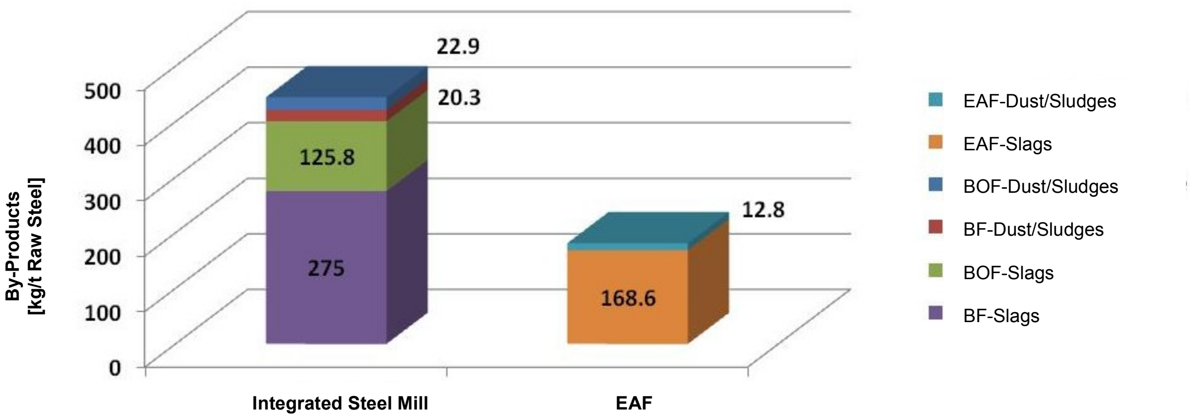

Figure 2: By-products of the crude steel production[8]

Since the blast furnace and the basic oxygen furnace on the one hand and the electric arc furnace on the other represent the majority of options to produce steel, the by-products of these are further examined in Table 1.[5][9][10]

Table 1: By-products of the crude steel production[5]

Blast furnace [$^{kg}/_{t\ crude\ steel}$]		Oxygen steel mills [$^{kg}/_{t\ crude\ steel}$]		Electric steel mills [$^{kg}/_{t\ steel}$]	
Slag	150-346.6	Desulphurization slag	3-40	EAF slag	60-270
Flue dust	3.4-18	BOF slag	85-165	Ladle slag	10-80
Flue sludge	2-22.3	Spittings	2.8-15	Dust	10-30
Foundry dust	0.6-5.1	Fine and coarse dust	0.75-24	Refractory waste	1.6-22.8
Refractory waste	0.1-13.7	Secondary Metallurgy slag	9-15		
		Metal extrusion slag	4-5.7		
		Scale (metal extrusion)	2.3-7.7		
		Refractory waste, etc.	0.05-6.4		

Most of the obtained slags already have functions nowadays. Since air-cooled ones often show a dense and hard structure, they are preferably used as additive in the construction industry. Granulated slag displays a glass-like, sandy texture and finds its primary use in the cement industry. Since the raw materials for iron and steel production vary depending on the production method and the actual steel type, the slags too show different chemical and physical behaviour, thus making it more complicated to find an adequate further use. Steel mill slags rather than blast furnace ones lead to this type of problem. Another aspect that plays an important role is the amount of free lime in the steel making slags which make it more difficult for the application in the construction industry. As a result, only 80 % of these slags find use in further processes, whereas blast furnace slags show a value of around 100 %.[5][8][11][12][13]

Recycling the accumulating filter dust and sludges constitutes an even more complicated problem. The high level of zinc makes the internal reutilization of fine converter particles and blast furnace gas sludges on the sintering belt an almost impossible task. Since the Waelz process in many cases does not offer an option due to the low level of Zn, sludges are favourably landfilled. Filter dust containing higher levels in zinc symbolises a special secondary raw material. A good example are the materials received from the electric arc furnaces in the steel production due to the elevated amount of Zn in the raw materials that in many cases consist of zinc-coated steel. These have a percentage of up to 40 % in total. In order to recycle this component, a lot of different methods have been developed, however, the Waelz process dominates with around 80 % of the total sum. Table 2 shows the production and the recycling of electric arc furnace dust in the year 2009.[5][14][15]

Table 2: Production and recycling of electric arc furnace dust[14]

	NAFTA	SEAISI	P.R.China	EU27	Other areas	World
EAF steel 2009 [Mt/a]	50.7	64.3	48.3	60.3	118.3	341.8
EAFD production [t/a]	760,100	1,157,000	724,200	1,024,400	2,129,300	5,795,000
EAFD recycling [t/a]	810,000	427,000	0	1,071,000	250,000	2,558,000
Waelz process share	735,000	270,000	0	831,000	210,000	2,046,000
RHF share	25,000	62,000	0	40,000	20,000	147,000
Other areas share	50,000	95,000	0	200,000	20,000	365,000
Zinc recovery [t/a]	186,000	98,000	0	246,000	58,000	588,000

Since electric arc furnace dust not only contains high levels in zinc but also hazardous substances such as halogenides in combination with dioxins and other metals such as iron, the processing in the Waelz kiln proves to be more difficult. Other methods such as the rotary hearth furnace, the PRIMUS- as well as the Plasma process and an adaption of the shaft furnace have also been developed to recycle these types of dust. Table 3 gives a summary of the currently available recycling processes for materials containing zinc, nickel and iron.[5][14]

Table 3: Residual materials and recycling processes[14]

Recycling processes		Waelz	RHF	PRIMUS	Shaft furnace	Plasma
Residuals containing Zn	EAF dust	X	(X)	X	(X)	X
	Foundry dust	X				
	Secondary dust	X				
	Zn smelter residual	X				
	Low-grade zinc ores	X				
	Brass dust	(X)				
	Zinc ashes	(X)				
	Alkaline batteries	(X)				
Contain-ing Ni	EAF dust (stainless)		X	(X)		(X)
	Catalytic converters		X	(X)		
	Ni-Cd batteries		X			
Containing Fe	EAF dust (low in Zn)	(X)	X	X	X	(X)
	AOD/BOF dust/sludge		X	X	X	
	BF dust/sludge		X	X	X	
	Sinter dust		X			
	Roll scale		X	X	X	(X)
	Roll scale containing oil			X		
	Scrap				X	

In order to determine and evaluate the specific properties, filter dust is subject to characterization. These analyses build the base for suitable recycling techniques.[5]

2.3 Characterization of Steel Mill Dust

Filter dust from electric as well as integrated steel mills provides a large set of different elements. Especially in the stainless steel section there are high contents of alloying elements such as nickel or chrome within the dust. Other, more general substances include elements like lead, chlorine, fluorine and various compounds with metals from the alkali group. In order to analyse the chemical and physical behaviour of these residuals, a lot of different tests have to be performed. First, the chemical composition is measured to discover all the elements present in the material. Table 4 presents the typical values for electric arc furnace dust.[5][16][17][18]

Table 4: Typical chemical composition of electric arc furnace dust[5]

Compound	FeO	Zn	Pb	SiO_2	CaO	K_2O	Na_2O	F	Cl
Weight-%	20-45	14-40	2-8	3-6	3-10	1.0-1.5	1.5-2.0	0.2-0.5	1-5

Whereas Table 4 offers values for EAF dust with a rather big tolerance, Table 5 gives a more detailed description of the elements contained in three different types of powder – electric arc furnace dust on one hand and basic oxygen furnace as well as cupola furnace dust on the other.[19]

Table 5: Comparison of the chemical composition of EAF-, BOF- and cupola furnace dust[19]

Weight-%	Fe_{ges}	Fe^{2+}	Fe^{3+}	Zn	Pb	Cu	SiO_2	CaO	MgO
EAF dust	16.9	0.13	14.8	38.7	4.5	0.42	7.4	2.9	1.9
BOF dust	43.3	11.1	15.4	17.2	0.16	0.02	1.7	11.2	2.7
Cupola dust	13.8	<0.1	13.1	29.9	0.02	0.05	23.8	8.5	1.4
Weight-%	MnO	Al_2O_3	K	Na	Cd	F	Cl	C	S
EAF dust	1.1	1.5	1.8	2.1	0.09	0.3	5.38	0.74	0.51
BOF dust	1	0.3	0.3	0.24	<0.02	0.03	<0.1	0.76	0.12
Cupola dust	0.9	3	1	0.47	<0.02	0.03	<0.1	5.17	0.47

When looking at basic oxygen furnace dust, it seems that iron appears in metallic as well as in oxidic state, whereas it is almost purely oxidic in the shape of Fe_2O_3 when regarding electric arc furnace- or cupola furnace dust. Knowing the contents of SiO_2, CaO, MgO and Al_2O_3 within the material, the basicity can easily be found out. EAF- and cupola furnace dust here show a very acidic behaviour with basicities between 0.3-0.4. However, only knowing the basicity of the material does not make it possible to estimate the melting behaviour which makes it necessary to perform a series of different other tests.[19]

2.3.1 Scanning Electron Microscopy

By means of the chemical analysis the potential of zinc and other substantial elements such as iron or lead can be discovered. The strong inhomogeneity within the samples constitutes the biggest problem in this step though. In order to investigate the structure for more details, scanning electron microscopes produce pictures of the probes and show the typical, complex structure of the dust. Figure 3 shows a mapping of electric steel mill dust.[5][19]

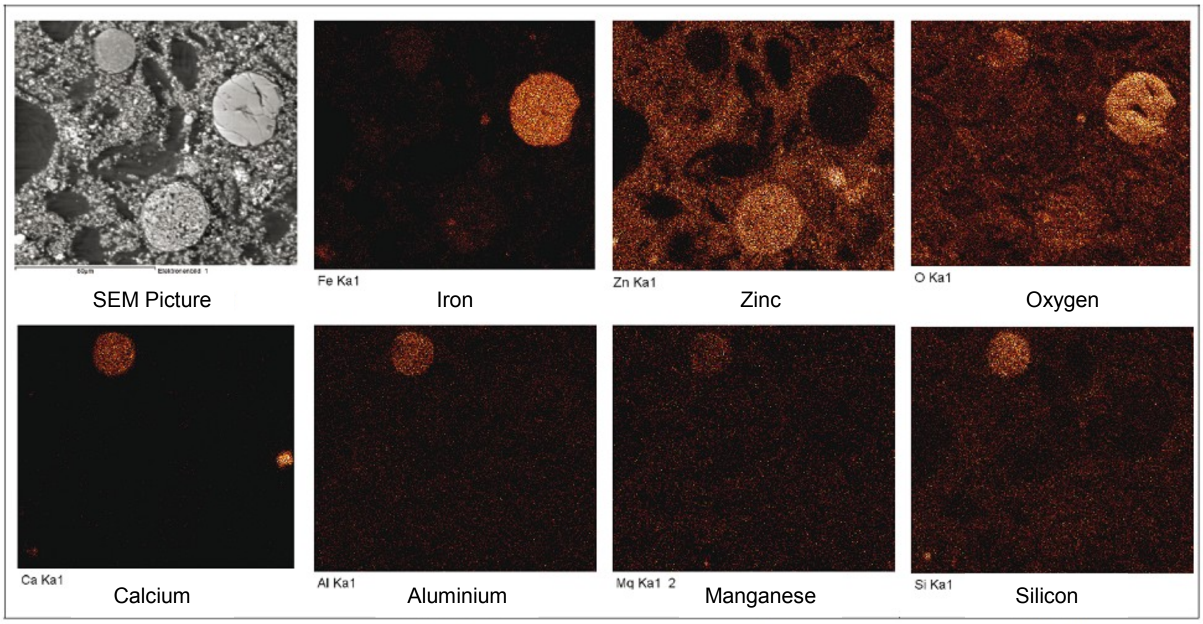

Figure 3: Scanning electron microscope mapping of electric steel mill dust[5]

On the basis of the mapping in Figure 3 one can only draw few conclusions regarding the melting behaviour of the material. The first picture shows a high content in iron which can be explained by the bubble bursting mechanism in the liquid metal bath. Reaching values of 14-38 % altogether, slag components play an important role in the chemical analysis. The pictures in the lower line for example show the presence of calcium, aluminium and silicon in the probe. However, once again there has to be mentioned that the inhomogeneity of the sample does not allow any generalizations and makes more analyses necessary.[19]

2.3.2 Hot Stage Microscope

Regarding further investigation of steel mill dust, the hot stage microscope offers a perfect additional method of analysis. While heating up the desired sample, it records the surface contours and then performs a software analysis. Figure 4 demonstrates different moments during a hot stage microscope testing of electric arc furnace dust.[5]

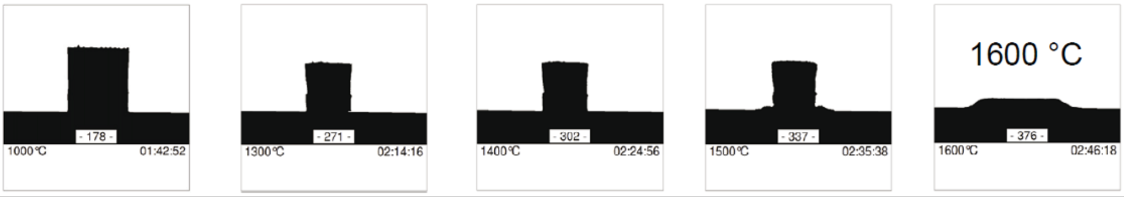

Figure 4: Analysis of steel mill dust using the hot stage microscope[5]

The five pictures in Figure 4 show the steps of a hot stage microscope analysis in atmospheric conditions. While the softening point of the electric arc furnace dust lies around 1200 °C, the flowing point cannot be detected until a temperature of around 1650 °C is reached.[19]

2.3.3 Bulk Density Measurement

To gain more information about the different types of dust, a bulk density measurement offers an additional analysis method. In order to interpret and plan the throughput and the size of a recycling facility, these details are essential. Table 5 compares the results measured by a device according to EN 23923-1. Whereas the bulk density of electric arc furnace- and basic oxygen furnace dust reach a value of around 0.54 g/cm³ which is typical for flue dust, the cupola furnace has a higher value, a fact that can be explained by the elevated ratio of fine particles.[19]

Table 6: Bulk density measurement of EAF-, BOF- und Cupola dust[19]

Bulk density	EAF dust	BOF dust	Cupola dust
g/cm³	0.54	0.54	0.94

Additionally to the described analyses, thermodynamic calculations are performed. One of the steps is to enter the residual material’s main components in a ternary system in order to find out the theoretical melting point and the phase distribution at a certain temperature. Other methods include grain size analyses, thermogravimetric tests as well as X-ray fluorescence analyses.[5]

3 Recycling Processes for Filter Dust

A lot of concepts regarding the recycling of filter dust from the steel industry and other metallurgical companies already exist and the most essential and common ones are presented in this chapter. The most important and by far most used one is the Waelz process which together with the SDHL technology is the "Best Available Technique" for the recycling of steel mill dust.[20][21] The principle of a typical recycling loop using the Waelz kiln as main vessel is shown in Figure 5.[22]

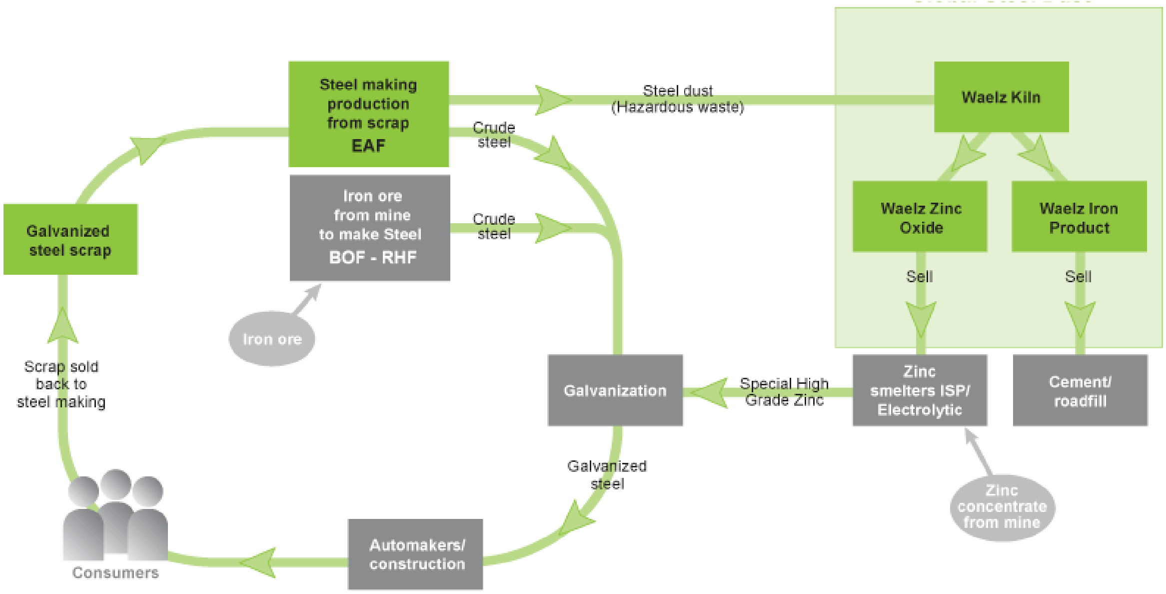

Figure 5: Principle of a typical recycling loop using the Waelz kiln[22]

Additionally to this method and the rotary hearth furnace, there are some more procedures that work on the one hand but are not established yet or play a subordinate role on the other:[5]

- Shaft furnace process (DK Recycling)
- ArcFume process (ScanArc)
- PIZO process (Heritage)
- Multiple hearth furnace (Primus – Paul Wurth)
- Melting reduction process in an electric furnace
- MEFOS concept
- RecoDust process (SGL carbon)
- ZEWA process (VAI)

3.1 The Waelz Process

Additionally to electric arc furnace dust (EAFD), other zinc containing residual materials such as dust from LD steel mills (BOFD), foundry dust, sludges and other residuals from the primary Zn production are recycled in the Waelz process. Furthermore, it takes care of accumulating material from the off gas treatment from foundry cupola furnaces together with electric steel mill dust from the galvanic industry, coke and lime.[23] Figure 6 illustrates a general overview of a Waelz plant.[24]

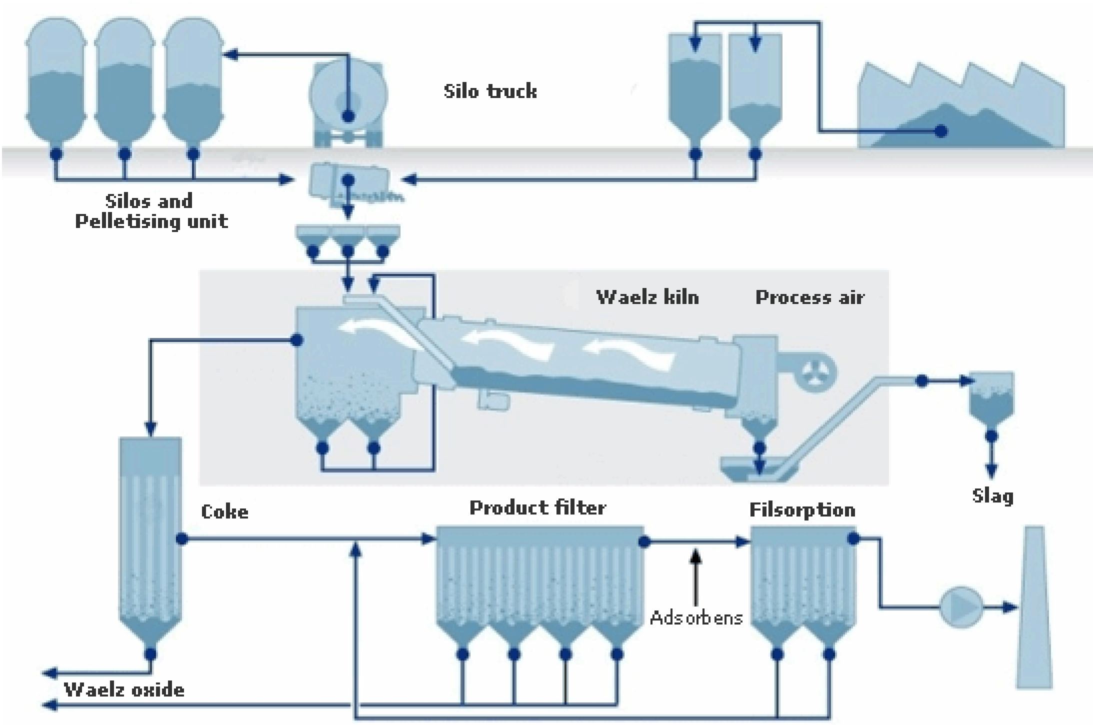

Figure 6: General overview of a Waelz plant[24]

Together with the reduction agent and further additives, the raw material is fed into a rotary kiln. Having reducing conditions within the kiln, the oxide compounds are reduced at a process temperature of about 1100-1200 °C which causes the zinc to vaporize from the lower part and reoxidize to ZnO in the upper one. This oxide moves to the feeding end of the kiln, is then separated from the exhaust gas by a suitable filter system and finally collected and sold as “Crude Waelz Oxide” (CWO).[5][25]

Befesa Zinc S.L.U. is one of the leading processors of zinc-containing filter dust from electric arc furnace steelmaking and other zinc-bearing residues and uses the optimized SDHL Waelz process in order to receive the desired end products. At the moment Befesa Zinc owns five production sites in Europe at different locations:[20][25]

- Befesa Zinc Duisburg GmbH in Germany
- Befesa Zinc Freiberg GmbH in Germany
- Befesa Zinc Aser A.S.U. in Spain
- Recytech S.A. in France as a 50 % shareholder
- Befesa Silvermet Turkey S.L. in Turkey as a 51 % shareholder

These steel dust section locations as well as the other main focuses like stainless steel and galvanization are displayed in Figure 7.[26]

Figure 7: Locations of Befesa[26]

The general basic as well as the improved SDHL Waelz process can be divided into three main steps that are presented in the ensuing chapters:[20][27]

- Material delivery and preparation
- Pyrometallurgical treatment in the Waelz kiln
- Off gas cleaning with Waelz oxide separation

3.1.1 Material Delivery and Preparation

The principal materials for the Waelz process are electric arc furnace dust as well as other zinc-containing residues which are delivered in trucks or by rail most of the time. Emissions are being reduced by using an airtight pneumatic conveying system for dry dust. In order to prove an efficient kiln operation, it is necessary to prepare the adequate mixture of the raw materials before introducing them into the furnace. Before the pelletizing step, the zinc-containing materials are mixed with other ingredients such as reducing agents and additives to provide slag. The right size of the pellets has to be determined and may be controlled by adding water. Once this step is completed, the pellets are ready for being charged into the kiln or for being sent to the storage area.[20]

3.1.2 Build-up of the Waelz Kiln

Usually Waelz kilns reach a length of 35-75 m and a diameter of 2.4-4.5 m, depending on the size of the construction, hence leading to a possible performance of 35,000-160,000 t every year. A typical furnace is about 50 m long and has an outer diameter of 3.6 m, while the inner one measures approximately 3.1 m as a reason of the refractory material. In order to ensure an adequate filling degree inside the vessel, the diameter decreases a little at the end by using more refractory lining. Depending on the length of the kiln, 2-4 supporting points are necessary to ensure stabilization and the rotation that normally runs at 1 turn per minute. The furnace's coat consists of 20-50 mm thick steel plates, underneath which there is an isolation lining and the refractory material containing mainly Al_2O_3. During operation crusts build up on the kiln's inner wall, a phenomenon which has to be fought against by melting them off every 500-1500 h. Beside the rotational movement, a decline of 2-3 ° ensures the transport of the input material which needs 4-10 h to pass through the vessel while the reaction gas leaves it a lot quicker in a counter current direction.[28]

3.1.3 Pyrometallurgical Treatment in the Waelz Kiln

At Befesa Zinc the Waelz kilns measure 40-65 m in length and 3-4.5 m in diameter. The constantly charged micro-pellets are moved by approximately 1.2 turns/min and remain inside the furnace for 4-6 h. The material mix enters the vessel at the top and is preheated by the hot reaction gases that leave the vessel. In the middle part of the Waelz kiln there is the actual reaction zone, where the reduction of the metal oxides takes place at a temperature of 1100-1200 °C. The first reaction to happen is the one between the reducing agent C and the oxygen from the gas phase, hence forming CO and CO_2, following the Boudouard equilibrium. The carbon monoxide subsequently reduces the oxides and presents their metallic form like Fe, Zn or Pb. Due to the combination of a high temperature and a low boiling point, many compounds such as zinc, lead but also chlorides and alkalis enter the gaseous phase, whereas the iron remains solid in the lower part. Since the non-solid phase offers an oxidizing atmosphere, zinc is reoxidized and leaves the kiln at the feed where it is led to a multi-stage exhaust gas treatment and a cleaning step. By applying the SDHL method and blowing air onto the charge at the end of the kiln, the freshly reduced iron is reoxidized and sets free the necessary energy for the reactions in the middle zone of the vessel. Figure 8 shows a cross-section of the Waelz kiln and points out the most important reactions concerning zinc which happen inside the tube.[20][29]

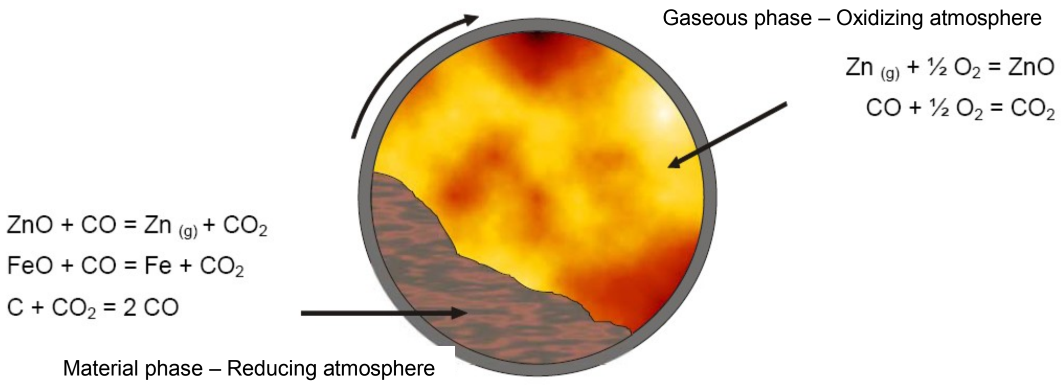

Figure 8: Cross-section of a Waelz kiln [28]]

On the one hand it is vital to achieve the highest temperature possible in order to guarantee a successful dezincing, on the other it must not exceed a certain value to avoid a molten slag which then might stick to the walls of the furnace. Additionally, liquid zones prevent the evaporation of volatile compounds such as zinc or chlorine. To guarantee an effective Waelz kiln operation, a lot of parameters have to be calculated in advance, however, empirical values play an important role as well.[20][29]

3.1.4 The SDHL Process

The SDHL method constitutes an improvement of the common Waelz process and is named after its inventors Saage, Dittrich, Hasch and Langbein. The main idea is the reoxidization of the metallic iron contained in the slag, hence providing additional energy at the end of the kiln. The created heat delivers enough energy to run the process without an additional oil or gas burner on the one hand and to reduce the coke rate on the other. The oxidization of the iron is achieved by selective blowing of air onto the slag using a lance that sticks into the furnace. This step allows an almost complete use of the slag's energy potential and leads to an end ratio of <10 % of iron and <1 % of carbon in the slag. Studies have shown that around 70-80 % of Fe is oxidized to FeO and less than 20 % to Fe_2O_3. In contrast to the basic Waelz process, a coke reduction of approximately 40 % can be achieved which leads to a decrease of CO_2 emissions as well as a performance increase of 25 %. Furthermore, the zinc recovery rises by 5 %. Table 7 demonstrates the achieved changes by listing the operating data of the two methods.[28]

Table 7: Comparison between the basic Waelz kiln and the SDHL method[28]

Process type	Flow capacity t/day	Zinc recovery %	Coke needed kg/t	Gas consumption Nm³/h
Basic Waelz kiln	165-170	86	270	180
SDHL method	200-210	91-96	160-170	0

3.1.5 Off Gas Treatment

The exhaust gas first enters a settling chamber for heavy particles that primarily consist of carry-over from the feeding step. Subsequently, the gas continues and is cooled by either air or spraying water. The Waelz oxide can then be collected in bag filters and sent to silos where it is packed. Apart from gathering the precious oxide, the cleaning system has to deal with the undesirable components as well. Volatile metals such as Hg, As or Cd as well as organic compounds like dioxins and furans are removed by an activated carbon filter. Before leaving the system, all critical values are measured and compared to the allowed limits which are stated in Table 8 for the different Befesa Zinc Waelz plants throughout Europe.[20]

Table 8: Limit values of the exhaust gas treatment of different Befesa Zinc Waelz plants[20]

Substance	Unit	Aser	Duisburg	Freiberg	Recytech
Dust	mg/Nm³	20	5	5	1 kg/h
As	mg/Nm³	-	0.02	0.02	5 g/h
As+Ni	mg/Nm³	1	-	-	-
Cd	mg/Nm³	-	0.02	0.5	5 g/h
Cd+Hg	mg/Nm³	0.2	-	.	-
Hg	mg/Nm³	.	0.05	0.05	5 g/h
No_x	mg/Nm³	300	350	200	50 kg/h
So_x	mg/Nm³	150	350	350	50 kg/h
Pb	mg/Nm³	-	-	-	100 g/h
PCDD+PCDF	ng/Nm³	-	0.1	0.1	0.75 g/a
Pb+Cr+Cu+Mn	mg/Nm³	5	-	-	-
Pb+Co+Ni+Se+Te	mg/Nm³	-	0.5	0.5	-

3.1.6 Products from the Waelz Process

The most valuable product received from the Waelz process is the Waelz oxide which is transported to silos for storage immediately after having been separated from the exhaust gas system. Additionally to a zinc content of 58-65 %, the end product contains small amounts of halogens such as chlorine or fluorine as well as alkalis like sodium or potassium. These elements play the limiting factor for a subsequent treatment in the hydrometallurgical zinc winning process due to the harmful properties of the halogens.[30] Chlorine attacks the aluminium cathodes as well as the lead anodes in the electrolytic zinc winning process. Additionally, the formation of Cl_2 can deteriorate the operational safety of the process. In order to guarantee safe production, chlorine values should not exceed 100 mg/l. Exceeding levels of fluorine mainly causes zinc to stick strongly to the Al cathodes which leads to problems while stripping. Due to a fluorine-zinc complex that is likely to occur, limits for this substance lie around 10-50 mg/l.[31] As a reason of a multi-step washing procedure, more than 90 % of these impurities are removed and the Zn content rises to values of around 65-68 %. Table 9 shows the typical composition of washed as well as unwashed Waelz oxide on one side and of Waelz slag on the other.[20][32]

Table 9: Chemical composition of unwashed/washed Waelz oxide and Waelz slag[20]

Weight-%	Unwashed Waelz oxide	Washed Waelz oxide	Waelz slag
Zn	55-65	65-68	<5.00
Pb	2.3-5.5	3.9-6.0	0.06
FeO	2.1-5.4	3.0-6.0	45.00
CaO	1.2-4.0	1.8-4.5	<26.00
MgO	0.2-0.5	0.3-0.6	<6.00
SiO_2	0.2-1.5	0.4-2.0	<10.00
Cl	0.1-6.4	0.05-2.0	0.10
FeO	0.1-0.5	<0.1-0.25	0.30
SiO_2	0.2-1.0	0.1-0.5	1.50
K_2O	0.05-3.9	0.04-0.1	0.10
Na_2O	0.3-3.1	0.1-0.3	0.60

The Waelz slag which continuously leaves the kiln at the end is usually cooled in a water bath. After an analysis it can either be used in the construction industry, sent to landfill or further processed to recycle the left-over zinc and other elements of interest such as iron or lead. In addition to these components, the slag mainly consists of lime and quartz. Any other volatile particles as well as the products from the reaction of carbon and oxygen leave the furnace at the feeding end together with the zinc oxide in the off gas. While air enters the Waelz kiln at ambient temperature, it leaves the construction heated together with the reaction gases at approximately 700-800 °C.[14][20]

Advantages of the Waelz process are the comparably low investment costs as well as the low energy costs and the simple technology. The high quantity of slag produced, elevated CO_2 emissions and a rather low quality of the zinc oxide represent the disadvantages. Usually the washing step leads to a higher content in the material's zinc content and the removal of many halogenides and alkali metals which dissolve as salts in the process. Adding Na_2CO_3 leads to an adjusted pH of around 8-9 and supports the dissolved metals to precipitate as carbonates. Plants that are able and allowed to discharge the leachate directly or slightly treated into rivers or the ocean own a considerable cost advantage over those having to afford and operate a crystallization unit.[5]

3.2 The RHF Concept

As an alternative to the Waelz kiln, rotary hearth furnaces (RHF) also play a role in the recycling of steel mill dust. There are numerous companies such as Midrex, Kobe Steel, ZincOx and Paul Wurth that use this technology in order to recycle the desired elements from zinc-containing materials. All different types, however, basically use the same principle. In addition to the “Crude Waelz Oxide” they also regain a fraction rich in iron, the so called “Direct Reduced Iron” (DRI). The pellets are prepared by mixing the Fe- and Zn-containing residues with coal after having been ground to a uniform size. Subsequently, the mix is pelletized to a diameter of 10-20 mm on a disk using water as a binder. In order to finish this step, the pellets experience a drying programme which helps them to stabilize on the one hand and also reduces the carry-over from the furnace on the other. In the next step the pellets are fed uniformly in one layer of low height into a rotating hearth furnace and moved through the process in a rotary form. Figure 9 demonstrates the concept set up by ZincOx.[5][14][33]

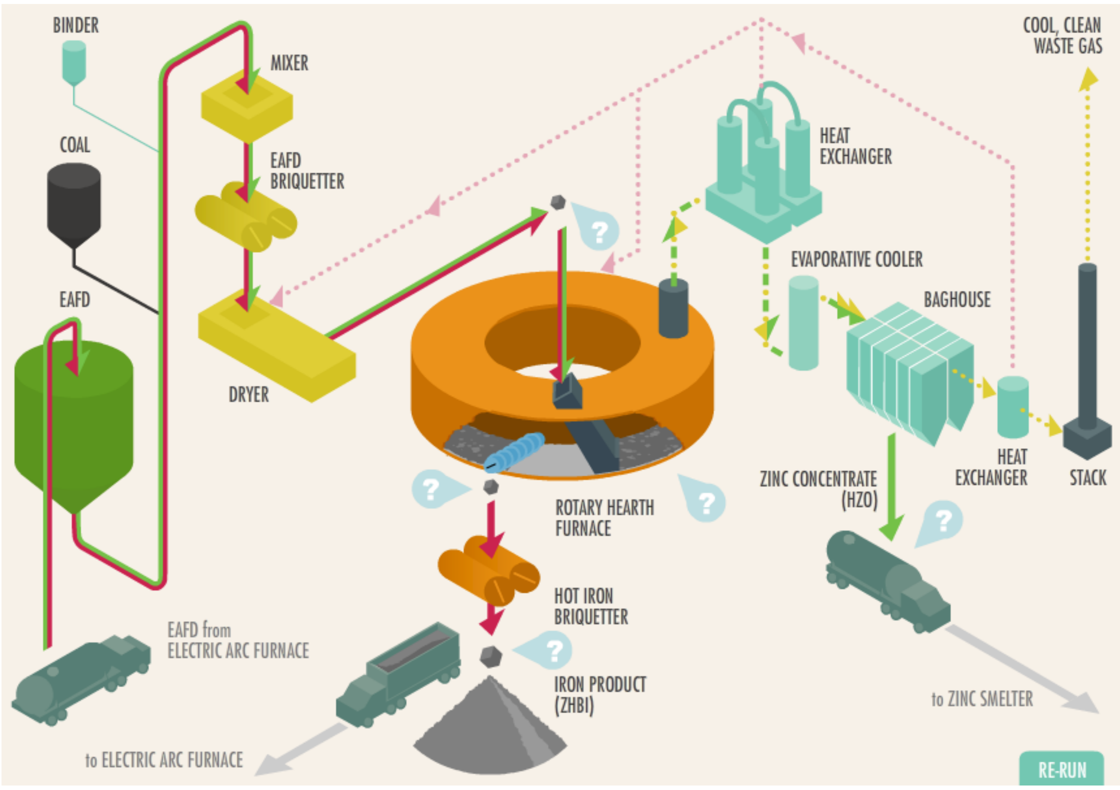

Figure 9: The RHF concept by ZincOx[33]

The temperature inside the rotary hearth furnace lies between 1200-1300 °C and the average treatment time is between 13-20 minutes which are needed for the material to perform a whole turn. Within the hearth there are fixed gas burners that heat up the charge at will, however, in the reaction zone no additional energy is needed due to the high content of CO which is burnt by the controlled addition of air. The zinc recovery is represented by a value over 97 %, whereas the metallization of the DRI is at around 90 %. Components such as lead, cadmium, partially sulphur, halogenides and alkali metals are volatilized as well and can be found in the exhaust gas. The reduced Zn reoxidizes inside the furnace and can be collected from the off gas by performing an additional treatment step.[5][14]

3.3 The PRIMUS Process

The heart of the PRIMUS process by Paul Wurth is a multi-hearth furnace heated by burners installed in the sidewall. The input material is charged on top and then moved to the lower stages with the help of rabble arms. Once arrived at the bottom of the furnace, the material can be discharged. A reducing agent such as coke or coal fines has to be charged together with the metal oxide in order to guarantee a successful reduction. Since there is constant movement inside the kiln, the different input materials do not have to be mixed beforehand. In the furnace there are different zones like the drying, the heating and the reaction zone. The CO gas generated during the step escapes from the material layer and can be burned straight away by installing an air injection inside the kiln. Since there are two areas, one for the material and the other for gas, two zones with different reduction potentials can be detected. The material layer has a high reduction potential due to the coke, whereas the gas zone offers oxidizing conditions. As a result of the post-combustion of the CO, volatilized oil and the volatile coal components, there is enough energy to maintain a temperature of 1000-1100 °C which is required for the process, however, it must not exceed these temperatures in order to prevent agglomeration of the solid particles inside the furnace.[14][34]

The PRIMUS method sets a focus on the input and recycling of zinc and lead containing waste material such as dust or sludges from the steelmaking industry. The metal oxides are reduced inside the kiln together with the iron oxide, however, they evaporate and leave the material layer. Since the gas zone offers an oxidizing atmosphere, the components immediately reoxidize and leave the furnace as ZnO, PbO and alkanine as well as halogene compounds together with the exhaust gas. These materials accumulate in the subsequent bag filter where they can be collected from time to time. On the one hand a highly metallized iron concentrate which may be used in the steel industry can be found at the bottom of the multi-hearth furnace and on the other a dust with a Zn content of around 50-60 % is achieved and can be sold to the zinc industry. Figure 10 depicts the PRIMUS process with its different stages.[34]

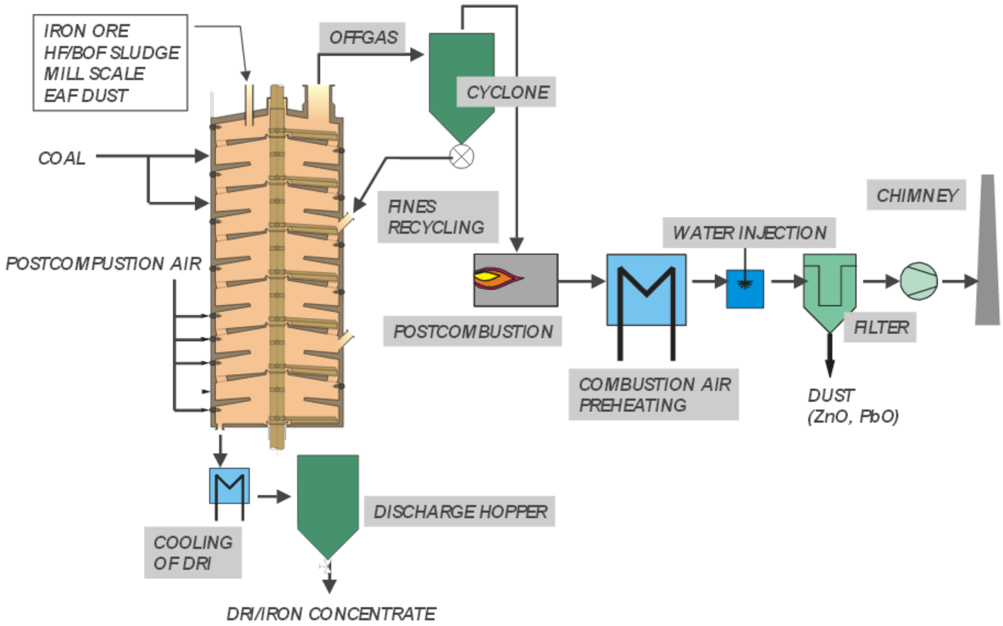

Figure 10: Principle of the PRIMUS process[34]

Since a purity rate of around 60 % does not provide a very high quality, there is an additional operation mode to the multi-hearth furnace. By separating the evaporation of the lead, alkali and halogen compounds in the first step, zinc oxides with purities over 90 % can be achieved. First, the steel mill dust is heated in the upper zone of the kiln at temperatures of around 950-1050 °C without the addition of a reducing agent. As a result of the high temperature, the desired materials evaporate and are extracted selectively. Having completed the first step, dispersed coke or coal fines are added and lead to a reduction of the zinc oxide in the lower part of the kiln. The Zn reoxidizes in the gaseous zone of the furnace and exits it via a second exhaust gas offtake which leads to a second filter bag designed for ZnO only. In Figure 11 the principle of this separated mechanism can be seen.[34]

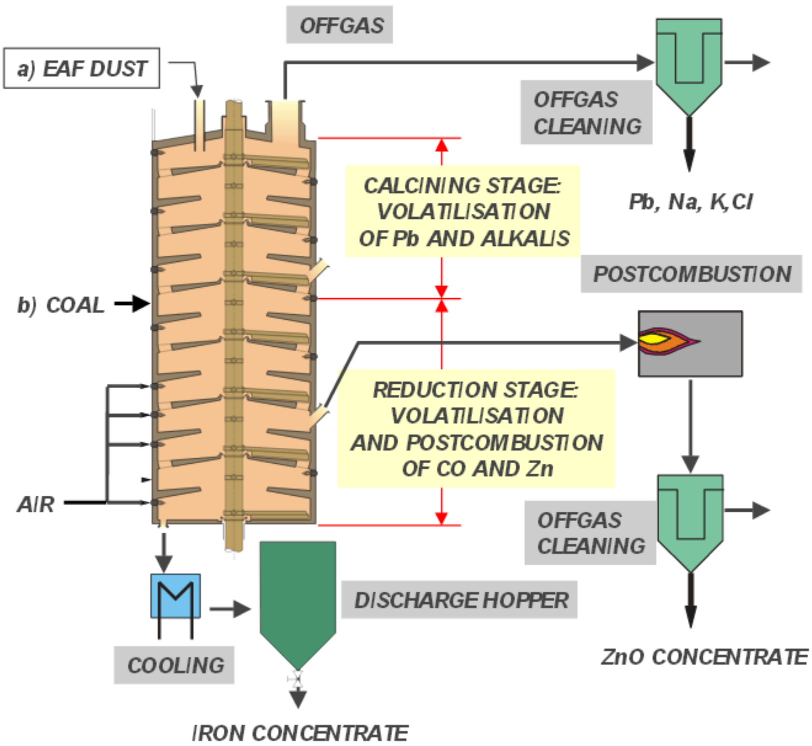

Figure 11: Principle of the separated mechanism in the PRIMUS process[34]

The second important part of the PRIMUS process is an EAF installed after the multi-heart furnace. It has the function of converting the DRI with an iron content of 50-80 % into a marketable iron alloy. Furthermore, it should produce a slag free in Fe and Zn which can then be sold to the construction industry.[35]

3.4 Comparison between the Recycling Methods

Additionally to Table 3, it is possible to compare the described methods for recycling zinc-containing filter dust. On the one side the raw materials as well as the end products play an important role, on the other the performance data of the different furnace types show interesting differences. Moreover, the economic side opposing the specific costs of the operating processes has a significant status concerning investment decisions. Table 10 gives a comparison of the different raw materials and end products of the Waelz process, the rotary hearth furnace and the PRIMUS concept.[14]

Table 10: Comparison of the raw materials and end products[14]

Process	Waelz	RHF	PRIMUS
Reducing Agent	Coke breeze Anthracite PET coke	Coke breeze Anthracite PET coke	High volatile coal
Flux	Sand or lime (limestone)	Binder	Binder (lime) Sand
Products	Crude ZnO Zn: 55-60 %	DRI Fe_{met} 80-90 % Fe_{tot} 30-70 %	Crude ZnO Zn: 52-60 % Pig iron
By-products	Slag	Crude ZnO Zn: 50-65 %	Slag

In contrast to Table 10, Table 11 gives information regarding the performance data of the three different methods. Important values are represented by the specific energy consumption and the Zn yield.[14]

Table 11: Comparison of the performance date[14]

Process	Waelz	RHF	PRIMUS
Specific consumption [1/DMT_{RM}]	200-300 kg coke breeze 20-250 kg flux/binder 150-200 kWh electricity ~5 Nm³ natural gas	180-250 kg coke breeze ~50 kg flux/binder ~150 kWh electricity 60-100 Nm³ natural gas	~280 kg coal ~50 kg flux/binder ~1050 kWh electricity ~5 Nm³ natural gas
Specific Production [kg/DMT_{RM}]	300-350 ZnO 600-650 Slag	50-100 ZnO 600-750 DRI	300-350 ZnO 250-300 Pig Iron ~300 Slag
Zinc yield	85-98 %	80-90 %	>95 %
Fe metallization	50-75 %	80-90 %	100 %

In addition to the technological and process input data, economic values constitute a very important factor as well. Therefore, Table 12 lists the capital as well as the operational expenditure for the Waelz process, the rotary hearth furnace and the PRIMUS method.[14]

Table 12: Comparison of the specific costs on a price basis of 2006[14]

Process	Waelz	RHF	PRIMUS
Specific CAPEX [US$/($DMT_{RM}$/a]	180-300 (200)	180-220	~500
Specific OPEX [US$/($DMT_{RM}$/a]	120-200 (170)	~100	250-300

To sum up the different data, Table 13 provides a final overview over the three different methods. On the one hand, the main target of each process is highlighted and on the other different advantages as well as disadvantages are compared.[14]

Table 13: Overall comparison over the methods[14]

Process	Waelz	RHF	PRIMUS
Main target	Recovery of zinc and non-ferrous metals	Iron recovery (integrated steel word residues back to BF)	Flexible iron and zinc recovery
Advantages	Mostly applied (80 %), simple, robust, known, BAT classified, acidic slag reusable, low CAPEX and OPEX, low energy use	Several installations for integrated steel work mix (low Zn), DRI used in BF, lowest CAPEX and OPEX, low energy use	Flexible in Zn and Fe content (Zn 10-30 %), coal instead of coke, additional production of pig iron (nearly BF quality), lowest slag quantity, stable and reusable
Disadvantages	Only crude ZnO produced, slag of low value basic slag unstable, lowest overall metal recovery rate	Operating installations for low Zn (<5 %) feed, 2 plants in USA for carbon EAF dust already idle	Complex technology, 2 industrial plants only, high CAPEX and OPEX, high energy use

3.5 Development of a Two-Stage Process

Nowadays there already exists a broad variety of recycling steel mill dust, however, most of the pyrometallurgical methods have a significant disadvantage. If the applied dust contains a high percentage of volatile impurities, these will finally accumulate in the end product, hence in the zinc oxide. Especially halogen-, lead- and alkali compounds play an important role in this mechanism because they are most likely found in dust from the electric steel industry high in Zn. Fitting in a washing circle improves the quality of the end product, however, the generated waste water can only be dumped economically in coastal areas. Aside from this topic, the recovery of other metals contained in the product is obtaining a major focus. While zinc always plays the main role in these recycling steps, the regain of lead or iron may enhance the economic feasibility of a new process. The University of Leoben has been developing a method, where the main focus lies on the regeneration of residual materials in a molten metal bath. Figure 12 displays the basic principle of this technique.[5][36]

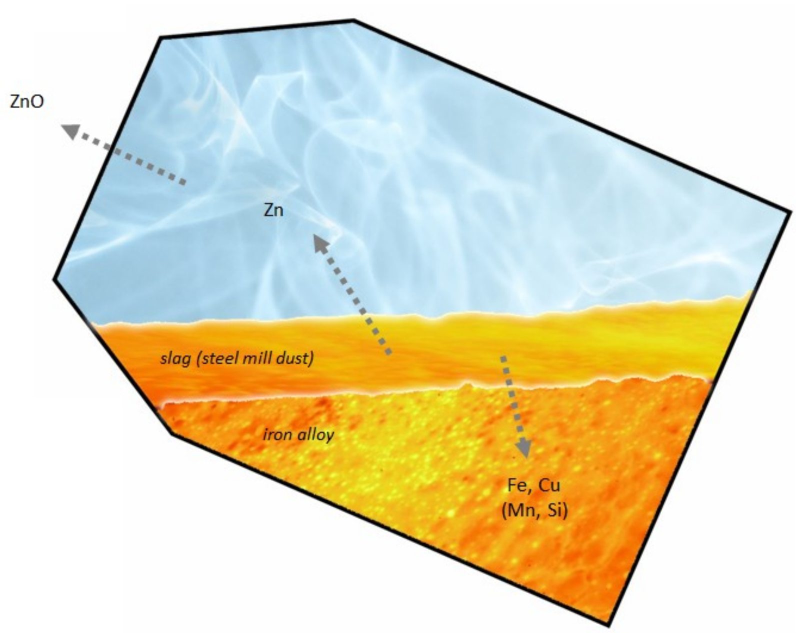

Figure 12: Principle of the recycling in a molten metal bath[36]

In the process the residual materials are introduced into the bath together with a reducing agent such as carbon which leads to a reduction of the oxides at the boundary layer of the slag and the molten metal bath. Some of the contained elements volatilize, whereas others accumulate in the bath or move to the slag above. What stays behind is a filter dust rich in Zn, an iron alloy and a stable slag that can be used in the cement or construction industry. Since this method also demonstrates just one step, the same problems like in the other processes occur. Together with the zinc a lot of undesirable elements volatilize as well, hence reducing the quality of the end product. In order to improve this, a second step has to be introduced. This so called Clinker process consists of a pyrometallurgical treatment at temperatures around 900-1100 °C in a neutral or slightly oxidizing atmosphere in order to avoid the reduction of ZnO. During this procedure, the zinc oxide remains inside the residual material, whereas the impurities like halogen-, lead- or alkali compounds volatilize and enter the exhaust gas system where they can be collected at the end. A considerable share of the halogen compounds leaves the furnace together with the generated lead-cadmium dust.[31] The result of this Clinker process is a high-quality base product for the next phase, the actual recycling step that is carried out in the molten iron bath. Figure 13 demonstrates a potential material balance of this two-step process dealing with the recycling of steel mill dust high in zinc. The top blown rotary converter (TBRC) constitutes a possible concept for both stages.[5]

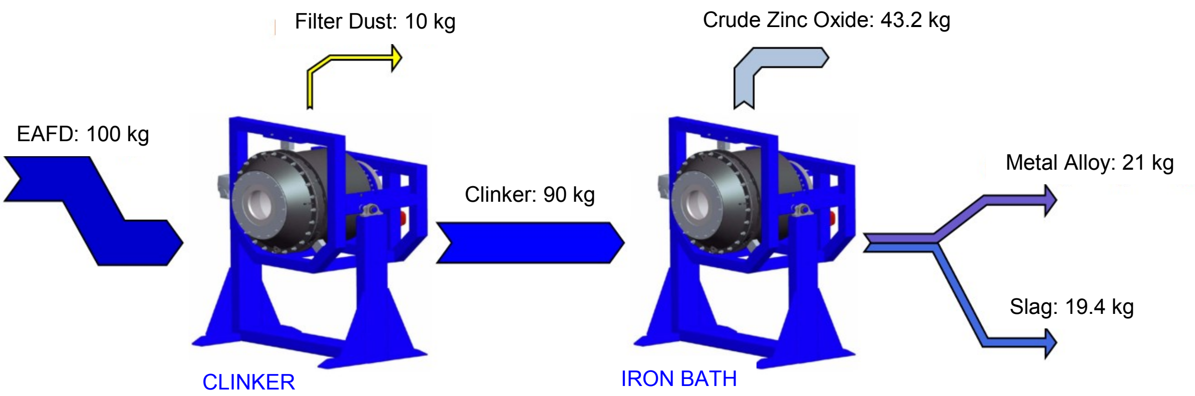

Figure 13: Possible material balance for a two-step recycling process[5]

Figure 14 shows the top blown rotary converter at the University of Leoben with a furnace capacity of around 80 dm³. As a result of a very flexible control system of the 75 kW burner that works with a mixture of methane and oxygen, both treatment steps can be performed in one single unit.[5]

Figure 14: Top blown rotary converter at the University of Leoben[5]

The quality of the produced TBRC-zinc oxide shows higher purity than the one generated in many other processes. Table 14 depicts the chemical analysis of three different methods, demonstrating the zinc oxide content of the material produced at the University of Leoben possesses a higher value than the other two.[5]

Table 14: Chemical Analysis of different oxides[5]

Weight-%	Zn	Fe	Pb	Cl	F	K	Na
Crude Waelz oxide	55-65	1.6-4.2	2.3-2.5	0.1-6.4	0.1-0.5	0.2-2.3	0.04-2.3
Washed Waelz oxide	60-68	1.5-3.9	9-11	0.05-0.1	0.1-0.2	0.1-0.2	0.1-0.2
TBRC zinc oxide	70.9	0.80	2.70	1.9	0.17	1.1	0.3

Since the removal of lead and fluorine in a cleaning step proves to be difficult, the demonstrated process represents a decent alternative compared to standard procedures. Using the new method, chlorine and the alkali metals are partially removed, however, their values still lie above those possible after an entire cleaning procedure.[5][37]

4 Achievements in the Treatment of Waelz Slag

This chapter briefly presents the most important aspects concerning the general properties of Waelz slag and additionally gives information regarding a possible recycling treatment, so companies should not be forced to landfill this product. Since there has not been too much research on this topic, only little is known about the method.

4.1 Characterization of Waelz Slag

The material which exits the Waelz process at the end of the kiln is commonly known as Waelz slag. Depending on the operation mode of the furnace, two different types are possible, the acidic and the basic one. Whereas in the first case a percentage of 27-37 % SiO_2 represents the average value, latter slag only shows 6-9 %. In contrast, the CaO percentage shows a rate of 13-25 % when looking at the basic material and 6-15 % for the acidic. Components such as zinc or lead do not show a dependency from the basicity and usually reach values of 5 % for Zn and 4 % for Pb.[38]

In order to use the Waelz slag for industrial purposes without any further treatment and therefore prevent landfill, two requirements have to be fulfilled. On the one hand aqueous conditions must not cause solution of the different slag components into the water and on the other mechanical properties such as density or grain size must meet the specific standards. In general, the end product requires an excellent elution behaviour which means a bad extractability of the different elements from the material. Relating to this requirement, acidic slags show better characteristics, however, they often do not meet the desired standards for being applied in the construction industry.[38]

4.2 Application of Waelz Slag

Originally, the total amount of accumulating slag from the Waelz process was sent to landfill. Restrictions concerning health issues as well as air and ground regulations were not dealt with and no significant depositing costs arose. By making these laws and conventions stricter, the necessity for a landfilling alternative seemed inevitable. Nowadays, the maximum amount of hazardous components follows different regulations. One of them that deals with the groundwater protection, only allows 0.05 % Zn and 0.03 % Pb within the material in order to be applied in the road construction industry. Additionally, the pH must not exceed values of 8-10 and the electric conductivity has to show a number of approximately 20 mS/m. These values are constantly measured and monitored by the respective companies themselves as well as by independent observers. Elements and compounds such as Zn, Pb, Fe, CaO, SiO_2, MgO, C and S represent some of the most commonly investigated slag components. On the other hand, a slag eluate test should regularly be performed in order to look for hazardous substances like F, Cl, As, Cd or Cr.[38]

By meeting the obligatory standards, the accumulating Waelz slag can be applied in following areas instead of being sent to landfill[38]:

- Base layers of pavement and bicycle tracks
- Road and path construction
- Parking areas
- Base layers of sports facilities
- Additives in the cement industry

4.3 Investigated Recycling Concept

Previously, there has been research on the topic of finding a concept for the recycling of Waelz slag at the University of Leoben. Since sending the material to landfill includes a significant cost factor, a technologically as well as economically feasible method represents the main target. Untreated slag usually includes a high percentage of leachable components and heavy metals such as zinc and lead for which reason depositing regulations are very strict and often expensive.[38]

The main idea for recycling the accumulating slag from the Waelz process consists of melting it in a converter in order to volatilize or inertize the undesirable compounds. On the one hand Waelz slag constitutes the main input parameter and on the other the resulting ash from the New Jersey process also displays an important factor. This material derives from the primary zinc industry and represents a waste substance that usually contains the elements with the corresponding amounts as described in Table 15.[38]

Table 15: Typical composition of ash from the New Jersey process[38]

Element	[%]
Zn	2-6 %
Pb	1-5 %
Cu	1 %
C	18-51 %
S	<1 %
Sb+Sn	<1 %
Fe_2O_3	19.5 %
SiO_2	9.5 %
CaO	2.6 %
MgO	1.3 %
Al_2O_3	5 %

Since many disposal sites are subject to repair, an alternative for depositing this ash is constantly sought for which reason the investigated recycling method also represents a possible solution. Due to the high carbon content this materials primarily serves as energy carrier. On the other side it also plays a role in the reduction of the zinc oxide that is contained in both input materials.[38]

The top blown rotary converter seems to provide excellent conditions for a successful operation. One significant advantage compared to other methods is the creation of major turbulences within the furnace which guarantees good reaction kinetics. In addition, the process can be controlled easily and should not imply unexpected problems. By heating and melting the mixture of Waelz slag and ash, the contained zinc, lead and sulphur volatilize and exit the vessel via the gaseous phase. At the same time, the remaining slag shows a silicate cover and therefore stabilizes the Pb that is left behind. When performing this process, the content of the undesired elements can be lowered and the limits for application in the road building industry are achieved. In addition, the amount of material that has to be sent to landfill decreases, which subsequently leads to a cost reduction when not meeting the required standards.[38]

When working with an ash amount of at least 33 % in relation to the total material, an autothermic process is achieved. By drying this component in advance, its ratio can be lowered to a value of only 25 %, hence resulting in a higher amount of Waelz slag at the same time. The addition of approximately 5 % SiO_2 helps to lower the slag's melting point and allows to work at a temperature of 1400 °C. In addition to the two solid input materials, the use of oxygen is essential in order to guarantee energy transfer as well as the desired atmosphere within the converter. As a result, the carbon and water cause a mass loss of about 30 % and the fact that the accumulating slag shows a higher density leads to an overall decrease of approximately 45 %.[38]

5 The Top Blown Rotary Converter

In general, convertors are vessels that provide space and the adequate protection such as refractories for all different kind of reactions. The top blown rotary converter symbolizes an advancement of the conventional top blown converter. In addition to the movement forced by the burner, the rotation of the vessel guarantees an excellent stirring of the metal bath as well as enhanced protection of the refractory lining. A typical TBRC can be rotated alongside its longitudinal axis and tilted alongside its transversal axis. Since the interior part measures approximately 80 dm³ and offers space for around 100 kg of treatable material, the construction needs to be firm and stable. The top blown rotary converter is especially used in the non-ferrous metallurgy and always contains an additional burner which guarantees the melting of the input material. It works with natural gas or methane on the one side and air or pure oxygen on the other. A big advantage concerning the TBRC is the fact that an oxidizing as well as a reducing atmosphere can be adjusted in the same vessel. Figure 15 provides the layout of a top blown rotary converter.[39]

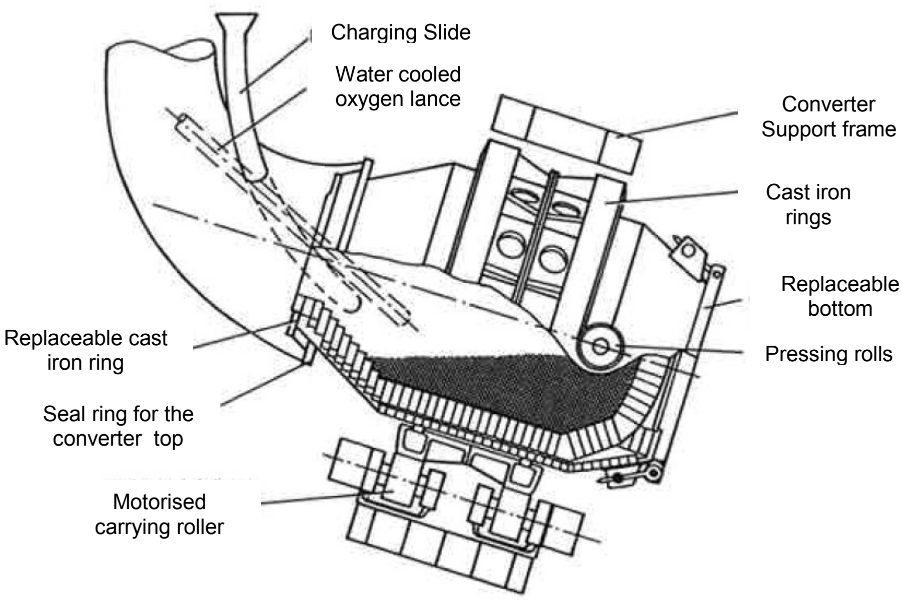

Figure 15: Top blown rotary converter[39]

In addition to the already mentioned details regarding the converter, Table 16 states and compares the differences and advantages of the TBRC in relation to a standard side blown converter.

Table 16: Comparison between the side-blown converter and the TBRC[39]

Function	Side-blown converter	Top blown rotary converter
Mixing of the reactants	Quite good, contact between gas and liquid phase only locally good, between the liquid phases moderately, O_2 enters bath with high potential which may lead to overoxidation	Good, turbulent bath as a result of the adjustable lance angle as well as gas speed and composition, O_2 can be introduced into the bath with high or low potential depending on the thickness of the slag layer
Temperature control	Complicated, temperature can only increase by overoxidation of the bath	Good, temperature can be controlled by oxidation of the bath or by additional burners
Heat distribution	Irregular, causes rapid destruction of the refractory materials in the nozzle area	Good, rotation of the converter leads to a quick heat adjustment and overall to a higher operating temperature
Bath movement	Quite good, turbulence caused by the bubble-column-principle influences the chemism and the temperature of the bath	Good, no influence on the chemism and the temperature of the bath
Control of the atmosphere above the bottom	Complicated	Good, O_2 potential may be adjusted at will

6 Calculation of the Parameters

Before performing the actual experiments, the parameters have to be calculated in order to guarantee the correct amount of input materials. First, the different resources are determined in an Excel file including the option for changing the content within the actual process. This step can be observed in Table 17.

Table 17: Possible amount of input materials for the process

Waelz Slag		10	kg		
Slag 1					
Compound	ZnO	PbO	Fe_2O_3	FeO	Fe
Slag 1 %	9.96	1.13	5.72	24.44	11.00
Additives		1.5	kg		
No 1					
Compound	ZnO	PbO	Fe_2O_3	FeO	Fe
No 1	0	0	0	0	0
Carbon		1.5	kg		
Sample 1					
Compound	H_2O	Ash	C_{Fix}	Volatile	SiO_2
Sample 1	0	1.7	96.21	1.87	0.17
Pig Iron		40	kg	**Ratio 1:**	**4**
No 1					
Compound	Fe	C	Si	Mn	P
No 1	94.72	3.9	0.33	0.81	0.09

Since all the materials contain a vast variety of compounds, only a small amount of the most significant ones can be seen in this table. The highlighted contents symbolize the variable parameters. Changing for example Slag 1 to Slag 2 would lead to another distribution in the compounds which were inserted into the file beforehand, whereas a different input weight of either the Waelz slag, the additives, the carbon or the pig iron would affect the following mass and energy balance. Given a ratio of Waelz slag to pig iron of 1:4, this fact implies a fixed content of the latter one in respect to the slag.

Performing an energy balance constitutes the next step in the calculation. Therefore, the energy used for heating the material on the one hand and the one for the reactions on the other have to be evaluated. All the steps are performed with the help of the thermodynamic program HSC 6.1. Assuming an input weight of the materials stated in Table 17, the energy needed to heat the batch from 25 °C to the desired process temperature of 1500 °C leads to a value of 62.93 MJ. In order to obtain the reaction energy, four different reactions are considered in Table 18.

Table 18: Energy needed for the desired reactions

Reaction	H per mol [J]	H per kg [kJ]	Factor [-]	H per kg Oxide [kJ]	Total H [kJ]
ZnO+C=Zn(g)+CO(g)	343275.30	3675.70	0.87	4218.21	4831.54
FeO+C=Fe(l)+CO(g)	134720.03	1606.54	0.86	1875.11	5270.89
Fe_2O_3+3C=2Fe(l)+3CO(g)	478723.30	2445.90	0.82	2997.79	1971.57
CuO+C=Cu(l)+CO(g)	-11056.79	-120.76	0.87	-139.00	-5.60

The step of summing up the different values shows that a total reaction energy of 12.07 MJ is needed. By adding the 62.93 MJ that are necessary for heating the batch and the determined reduction energy of 12.07 MJ, a total amount of 75.00 MJ can be determined. In this calculation step ideal processes are assumed and no losses included.

In the burner, methane and oxygen are used for which reason an evaluation of the correct gas amounts depicts the next step. Once again, the heating energy for the two gases on the one side and the energy provided by the exothermic reaction on the other have to be considered. By comparing the 75.00 MJ needed altogether to the necessary energy supplied, an amount of 2.79 Nm³ of pure methane provides the correct energy result for a total input of 10 kg Waelz slag and 40 kg pig iron granules. Calculating the weight of carbon needed for the different reduction equations constitutes the last step in the energy balance. Looking at the reactions in Table 18 and bearing in mind that the C content is already contained in the bath due to the other materials, the stoichiometric amount of carbon can be determined. For the reduction processes a total amount of 0.79 kg of C is needed, whereas another 2.28 kg are necessary to guarantee a ratio of approximately 4.3 % within the bath in order to keep it liquid. Due to the fact that the pig iron and the Waelz slag contain some carbon as well, the calculation leads to an amount of 1.32 kg needed for a successful operation, however, for the actual experiment the losses which are high at these temperatures and at the oxidizing atmosphere are kept in mind. These factors directly influence the process quality and therefore the characteristics of the end product.

The mass balance is carried out by regarding the input amounts stated in Table 17. For this step, the different end products have to be considered. The elements Fe, Cu, Si and Mn for example are assumed to end up in the iron regulus after the reaction. Additionally, the fixed minimal amount of 2.06 % C is added to this section. Since sulphur partly remains in the metal and the other part leaves the process in the off gas its exact distribution cannot be determined. On the other hand components such as ZnO and PbO play an important part in the formation of the filter dust. Compounds that supposedly enter the slag are CaO, MgO,

SiO_2, Al_2O_3. MnO displays a rather interesting component in the process. While it can be found inside the slag when performing the reduction in a top blown rotary converter, the result in an electric arc furnace would vary. For this aspect the oxygen potential plays a major role. Whereas the EAF shows a strong reducing potential and would therefore reduce the manganese to its metal form, the TBRC does not guarantee such a high potential which is why the Mn can still be found in the slag after the reduction step is finished. Same thoughts may apply to the silicon in the process. This fact impressively shows the importance of choosing the adequate reaction vessel in order to perform a standardized process that guarantees a constant product quality. Last but not least the rest of the carbon is assumed to react to CO and exit the furnace together with the chlorine impurities. Considering all these components and reactions, the theoretical mass balance can be carried out, leading to the results shown in Table 19.

Table 19: Results from the theoretical mass balance

Input		
Iron Bath	40	kg
Waelz Slag	10	kg
Additives	1.5	kg
Carbon	1.5	kg
Output		
Iron Alloy	43.51	kg
Filter Residues	1.28	kg
Exhaust gas	3.29	kg
Slag	4.86	kg

The comparison of the amount of the input materials with the output sum shows an almost perfect balance of the different masses. As a result of the reactions, the redistribution from the Waelz slag components to the iron alloy, the slag and the filter residues can be observed. These outcomes represent reference points for the following actual experiments. Figure 16 displays a Sankey diagram of the theoretical mass balance.

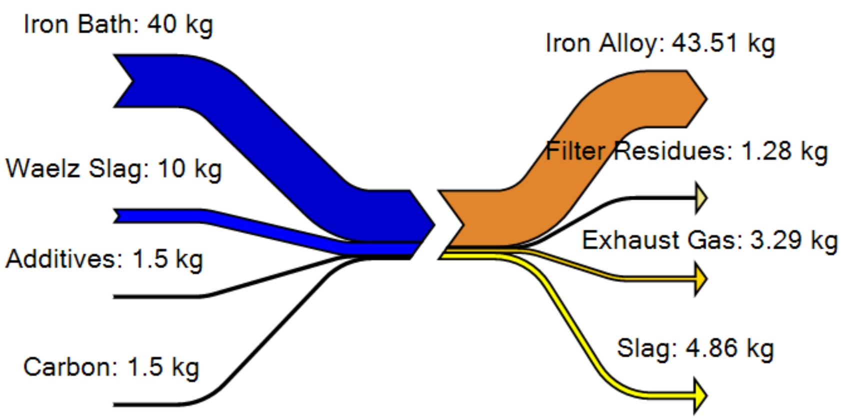

Figure 16: Sankey diagram of the theoretical mass balance

The Sankey diagram in Figure 16 also demonstrates the importance and necessity of a standardized and smoothly running operational process. If unexpected turbulences and errors occur, the product quality suffers and the distribution of the different elements is not as described in the mass balance. In the worst case the most valuable component zinc is not reduced and can therefore not be collected in the filter dust, whereas the components iron alloy and slag are not fully separated and can only be collected together. By performing actions concerning the process quality, a constant and stable operation mode is guaranteed. In the case of the new recycling concept a failure mode and effect analysis constitutes a first and logic step in the right direction.

7 Experiment Realization

After having calculated all the important process parameters in advance, the raw materials were weighed and three different trials were performed on the top blown rotary converter at the University of Leoben. During the experiments the focus was also set on providing stable and therefore standardized process conditions.

7.1 Trial I

In order to guarantee constant parameters for the experiment, the TBRC had to be cleaned before the first setup. Starting the process, a mixture of pig iron and blast furnace slag was introduced into the oven and heated inside for a certain time. During this step, the Fe had the function of collecting all the impurities from the refractory material. It was then tapped together with the slag and left behind a clean rotary furnace.

Before starting the actual experiment, a calculation of the input materials took place. By using the generated Excel file, all the data could be determined. Therefore, 40 kg of pig iron granules served as base material for the iron bath. Aiming at a ratio of 1:4 regarding the amount of Waelz slag used in the process, this meant 10 kg of the latter material. In order to guarantee a carbon content of in-between 2.06 % and 4.3 % on the one hand and a complete reduction of the oxides on the other, C had to be added in the form of coke as well. Since this material has a significant burn-off, 1.5 kg were applied instead of using the stoichiometric 1 kg in order to achieve a percentage close to 4.3 %. However, to carburize the pig iron bath without reducing the not yet introduced Waelz slag and hence trying to reach a carbon content of approximately 4.3 %, 0.5 kg of C was added in advance. In order to minimize the risk of errors and guarantee a constant process quality, these steps were performed by the same person and the resources were used as well as observed in the same way each time. Figure 17 displays the used raw materials, consisting of pig iron granules, Waelz slag and coke.

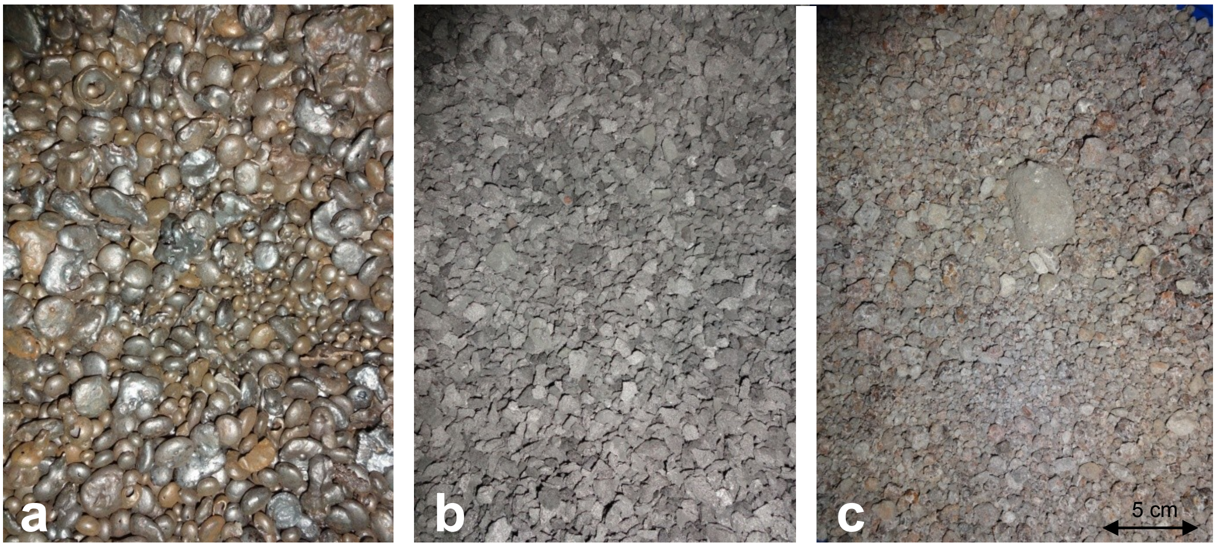

Figure 17: Raw materials – pig iron granules (a), coke (b) and Waelz slag (c)

The burner set-up showed a gas flow rate of between 12 and 15 Nm³ per hour, depending on the heating speed needed at the particular moment. The reduction grade was controlled by λ, the ratio of oxygen compared to the energy source, methane. Beside this definition, the ratio of the two gases can also be calculated by the formula "$\%CH_4 = 1/(1-2*\lambda)$". Starting at λ=1, a modification to a ratio of 0.9 and later a further decrease to 0.85 took place. Considering results from former tests, a rotational speed of three turns per minute represented the best choice for the rotary converter.

The actual experiment started by filling the rotary furnace with 40 kg of pig iron granules. After a heating period that happened in order to melt the iron, the temperature ϑ was measured. Having reached a ϑ of around 1545 °C and completely molten the iron, a so called Lollipop sample was taken. This metal piece displays "Number 1" and can be seen in Figure 18. In order not to mix up the different materials and hence deteriorate the information value, these samples were marked straight after having been drawn.

Figure 18: Lollipop sample 1

The next step consisted of introducing the Waelz slag/coke-mixture into the process. The complete mix was divided into three parts and entered at different points. Furthermore, the second and the third dose also included 0.75 kg of quartz sand which served as additive. After waiting for some minutes, as well for the melting of the new material as for the actual reduction, the temperature was analysed again and showed a value of 1537 °C. Furthermore, another Lollipop sample was taken and the TBRC was filled with the second part of the mixture.

After some more time, the whole procedure was performed again. Given a temperature of 1464 °C, sample 3 just consisted of slag due to unsuccessful sample drawing. Since the temperature dropped below 1500 °C, the iron bath showed a stickier consistence. This behaviour can also be explained by a raise of the melting temperature due to the lower content of carbon which had already been used in the reduction process. In order to improve the flowability of the mass, the temperature was raised again before charging the third and ultimate part of the slag/carbon-mixture. Once again, after the filling step at about 1519 °C the materials reacted intensely which is illustrated in Figure 19.

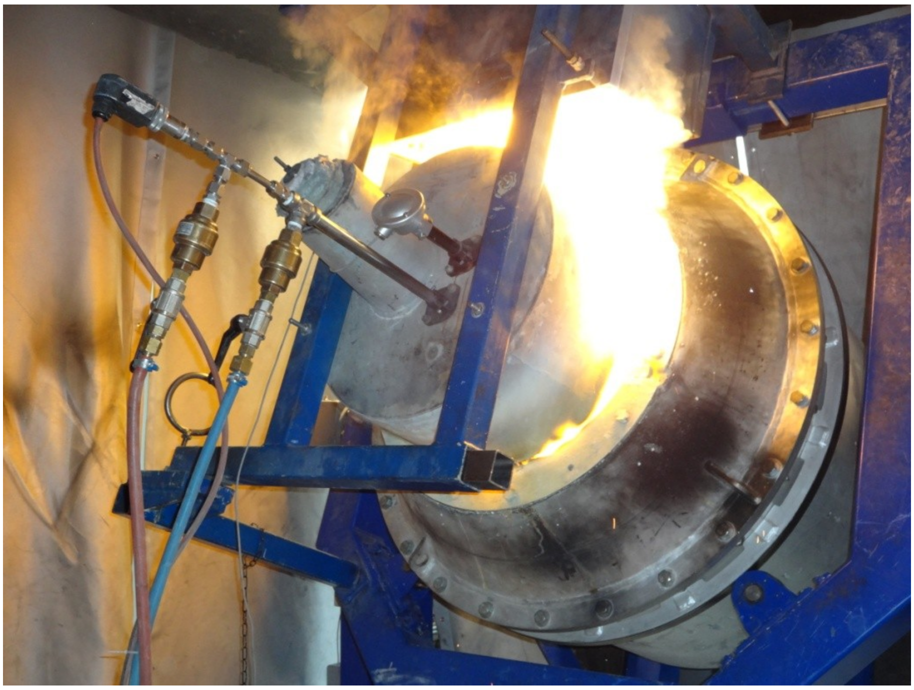

Figure 19: Reaction process in the top blown rotary converter

As some of the Lollipop samples had not been effective, a second way of collecting metal probes came into operation. Additionally to the usual sampling, a small part of the metal bath was scooped and put into a mould each time after measuring. Sample 4 constituted an excellent example of these scooping probes. Including the third filling step, all evaluated raw materials had been inserted into the rotary converter, so the process basically just needed some more time to guarantee a complete reaction.

Constantly keeping λ at 0.85 and slightly increasing the flow rate led to a rising temperature inside the converter. Consequently, sample 5 was drawn at a temperature of 1551 °C, also symbolising a perfectly liquid iron bath again. During the scooping of the last probe 6, a ϑ of 1602 °C was detected, hence demonstrating an effective yet a little exceeded operation mode for the converter. In order to achieve a successful finish of the experiment, the process was given some more time to cool down to 1545 °C and to guarantee a completed reaction before the tapping. Figure 20 demonstrates this last step.

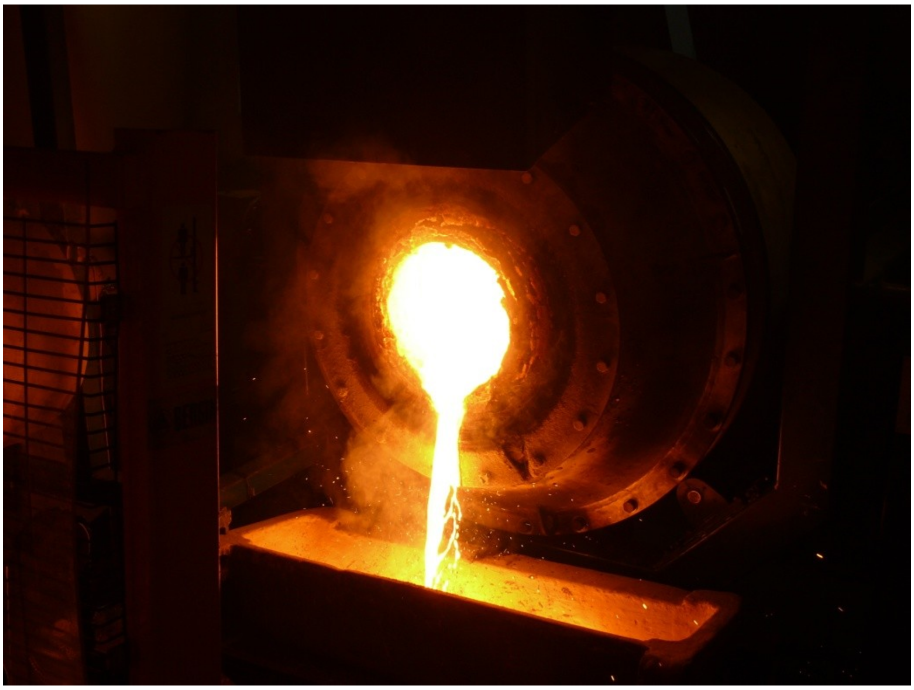

Figure 20: Tapping of the top blown rotary converter

7.2 Trial II

Two days after the first experiment the next trial using the top blown rotary converter took place. Once again, the raw materials consisted of 40 kg iron granules and 10 kg Waelz slag in order to guarantee standardized and comparable conditions. However, since the first day had shown a significant coke decrease during the first phase, a different strategy for this material was evolved. Instead of introducing all the coke at once, 1.5 kg were inserted into the iron bath one hour after having inserted the pig iron into the TBRC, followed by another 2.5 kg after 25 minutes. These doses entered the molten metal at different times in order to reduce the burn-off and to keep the exhaust gas temperature at adequate levels. An exceeded use of carbon would have led to an increased formation of CO and hence produced more exothermic energy which subsequently would have led to an elevated off gas temperature that damages the filter in the exhaust gas system. Lambda was set to a stable value of 0.8 throughout the experiment, however, when carbon was added, it was lowered in order not to oxidize all of the C before dissolving in the alloy and to guarantee adequate conditions for the reduction.

The first third of the Waelz slag was then charged into the bath without coke due to an elevated gas temperature which would once again have led to a possible damage in the exhaust gas system. Following the schedule, the second and the last third were mixed with 1 kg of coke before entering the iron alloy. Altogether this meant a total sum of 6 kg coke, constituting around four times more than the actual stoichiometric amount of carbon of

1.38 kg needed. Guaranteeing a higher level of this element in the molten bath, the exhaust gas also showed raised amounts of carbon monoxide, hence suggesting a different control pattern for the tapping point. 240 minutes after charging the converter, lambda was set to 0.9 and after another 30 minutes, the iron alloy showed a sticky behaviour for which reason the burner gas flow rate was raised to the maximum of 20 Nm³ in order to prepare a less viscous bath for the tapping process. 280 minutes after starting the experiment and taking numerous iron as well as slag samples the tapping was performed.

7.3 Trial III

Since the top blown rotary converter already had the needed process temperature, a third experiment was performed immediately after the second one. The main difference compared to the trial before depicted the use of petrol coke instead of the preceding coke breeze. Since this type of reducing agent displayed a finer powder it showed a bigger surface which led to a boosted reaction when entering the bath, as can be seen in Figure 21.

Figure 21: Intense reaction using petrol coke

Due to the fact of a high CO ratio compared to the CO_2 in the former experiment, the first carbon part was only added together with the first third of Waelz slag. The second addition of petrol coke led to the same intense reaction as the latter one which is why the exhaust gas temperatures showed high values. As a result of the high temperature no additional carbon was added to the last third of Waelz slag. Instead, the reaction was given some more time while continuously taking probes of the metal bath and the slag. 170 minutes after starting the third trial, the tapping happened, making visible the process slag on the liquid iron alloy in the mould which is shown in Figure 22. Here, the bright orange zones mark the pig iron that can be found below the slag. Whereas on the one hand the darker orange areas mark the hot and still liquid slag, the cooled solid slag is characterized by its black colour.

Figure 22: Slag on liquid iron bath in the mould

8 Experimental Results

After having completed the three different trials, iron as well as slag samples were arranged and sent to the laboratory in order to perform spark spectroscopy tests for the metal regulus and wet-chemical analysis for the slag to investigate the chemical composition. Together with the obtained data from on-line temperature and gas measurements during the experiments and the calculated tables, different results can be obtained.

8.1 Results from Trial I

The first part of reproducing the experiments consists of analyzing the temperature and concentration changes of different interesting elements at various times. The values of temperature measurement using a lance during the trial are displayed in Table 20. On the one hand each sample taken at a certain time is stated, on the other the measured ϑ inside the bath can be seen. Sample 3 is not included in the table due to an unsuccessful Lollipop sample drawing during the experiment.

Table 20: Sample, time and temperature from the first trial

Sample [Nr.]	Time [min]	Temperature [°C]
-	0	1507
1	72	1548
2	93	1538
4	113	1465
5	148	1519
6	182	1552

In addition to the different time measurements using a lance, a continuous on-line system based on an integrated thermocouple in the top blown rotary converter gives a more precise view on the temperature development throughout the process. Table 21 gives an overview of the development of different elements such as carbon, silicon, manganese, copper, zinc and lead. The results derive from the wet-chemical analysis on the one hand and from the spark spectroscopy tests on the other.

Table 21: Chemical composition of important elements in the first trial

Sample [Nr.]	Time [min]	C [%]	Si [%]	Mn [%]	Cu [%]	Zn [%]	Pb [%]
-	0	3.7900	0.8200	1.2900	0.0100	0.0000	0.0000
1	72	2.0000	0.1520	1.1000	0.0160	0.0054	0.0039
2	93	2.2600	0.0000	0.4460	0.0200	0.0035	0.0000
4	113	0.0300	0.0019	0.0700	0.1140	0.0030	0.0000
5	148	0.0200	0.0000	0.0240	0.1470	0.0099	0.0000
6	182	0.1500	0.0000	0.0200	0.1650	0.0036	0.0037

By combining the time measurement from Table 20 with the different chemical compositions from Table 21 and the on-line temperature values, a new informative diagram can be created as can be seen in Figure 23.

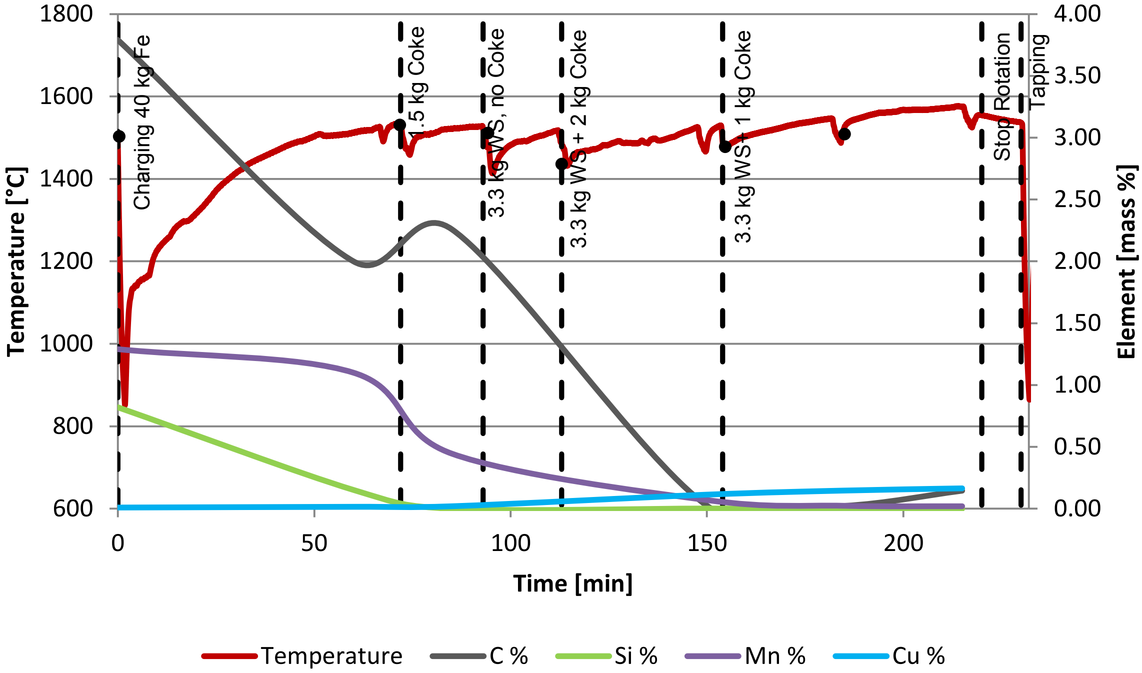

Figure 23: Measurements during the first trial

Looking at the diagram, different observations are possible. While the temperature values are demonstrated on the left side of Figure 23, the percentage distribution of the different elements can be seen on the secondary axis. The temperature measurements from Table 20 performed with a lance are additionally included in Figure 23 and are marked with black dots. As can be seen, the values of the two different measuring methods show almost the same result. A very significant observation is the fact that using a slightly over-stoichiometric amount of carbon leads to a high burn-off and hence not enough C which is supposed to reach values between 2.06-4.3 % throughout the operation. The silicon as well as the manganese completely move to the slag as described in the experiment realization chapter, whereas the noble copper can be found inside the metal alloy. The temperature remains quite stable within the 1500 °C area and just approaches higher levels at the end of the trial.

Additionally to the continuous measurements, a part of the obtained Fe regulus was cut off and sent to the laboratory to determine the chemical composition. The most important elements contained in the final product are demonstrated in Table 22.

Table 22: Chemical composition of the Fe regulus from the first trial

Element	Fe	C	Mn	P	S	Cr	Ni	Mo	Al	Cu
[%]	99.6060	0.0210	0.0230	0.0110	0.0530	0.0063	0.0330	0.0072	0.0033	0.1630

Figure 24 shows the metal regulus that is presented in Table 22 together with its corresponding scale. The surface confirms the metallic characteristics, while small parts of slag can still be found as well.

Figure 24: Surface of the Fe regulus

Having carefully drawn the samples and weighed the heavy main regulus as well as other smaller iron pieces, slag components and the filter dust from the bag filter, a mass balance supplies more detailed information regarding the mass flow and distribution. Looking at the values in the Sankey diagram in Figure 25 and comparing these to the ones in Table 19 and Figure 16 prove major iron losses.

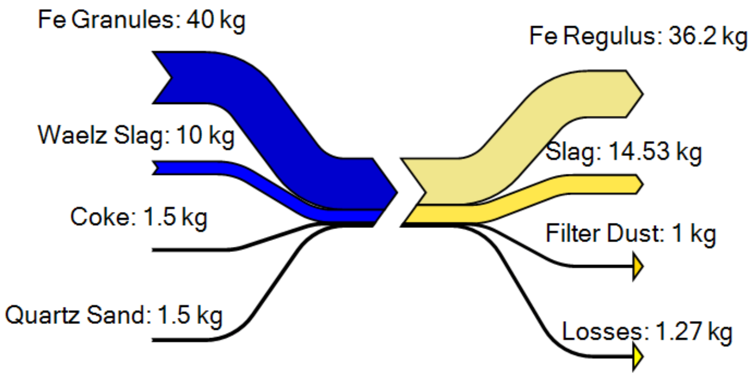

Figure 25: Mass balance from the first trial

These losses may be justified by different reasons. On the one hand the slag demonstrates an elevated weight which leads to the conclusion that a great amount of the iron that was supposed to be part of the regulus is still contained in the “non-metallic” compound. Due to the tapping at high turbulence, during which both phases left the converter at the same time, a full separation step could not be guaranteed. After further investigation and an additional grinding step for the slag, this assumption was given proof. Table 23 gives further information regarding the slag composition.

Table 23: Chemical slag composition from the first trial

Component	[%]
Fe	31.50
Pb	0.01
Zn	0.81
Al_2O_3	6.11
CaO	13.10
MgO	11.30
MnO	4.98
SiO_2	19.30
Fe_{met}	1.20

As can be seen, the metal Fe represents the biggest part, while the compounds CaO and SiO_2 also play a significant role and cause a basicity of 0.68. Figure 26 summarizes the distribution of the most important elements within the slag in relation to each other.

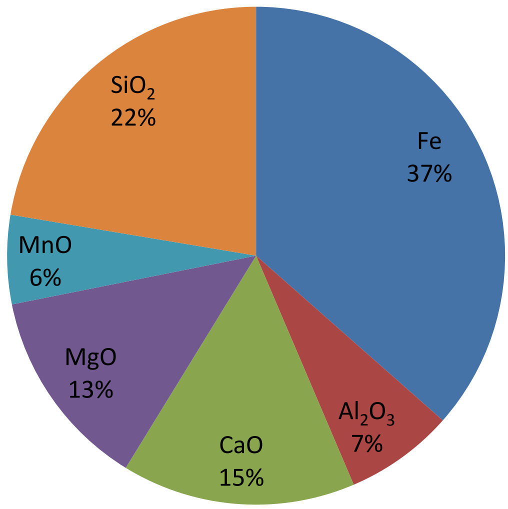

Figure 26: Chemical slag composition from the first trial

Another error source falsifying the results constitutes the fact that the weight of the filter dust containing ZnO and PbO is rather inaccurate. Since the construction of the converter and its facilities is quite complex and various experiments are performed using the same exhaust gas system, a precise measurement of these types of dust is not possible which leads to a certain carryover. One component whose weight could not be identified represents the off gas. Since it continuously exits the furnace containing mainly carbon monoxide as well as carbon dioxide, no further details about the losses may be given. Keeping in mind all of those error sources, the sum of 51.73 kg after the experiment shows an accurate result and underlines the process quality.

8.2 Results from Trial II

Like in the first trial, the beginning step of investigating the experimental results consists of analyzing the change of the temperature over time. Table 24 represents these alterations in the same manner.

Table 24: Sample, time and temperature from the second trial

Sample [Nr.]	Time [min]	Temperature [°C]
-	0	1549
1	62	1528
2	89	1456
4	136	1430
5	155	1400
6	192	1405
7	214	1461
8	245	1480

As in the first run, a diagram with the temperature development on the one side and the distribution of certain elements on the other can be created. Figure 27 shows the on-line time measurement including the significant steps having taken place during the process as well as the ϑ values from the lance and the changing percentage distribution of carbon, silicon, manganese and copper.

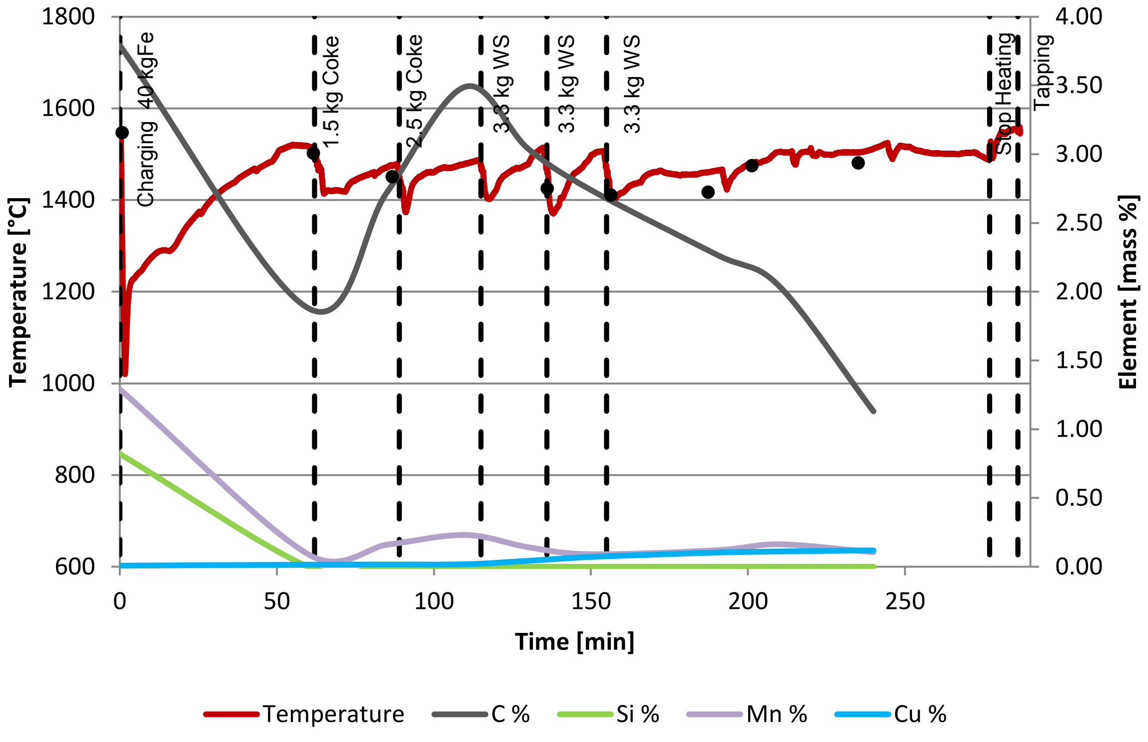

Figure 27: Measurements during the second trial

The development of the graph exactly represents the experiment's description. A slight decrease of the temperature may be observed every time after adding either component to the bath, a fact which can be justified by the detail that the input material had not been heated in advance and hence needed heating energy in order to reach the process temperature. Overall the second experiment shows quite a stable distribution of ϑ within the vessel, however, when looking at the values measured manually using a lance in Table 24, drops of up to 100 °C can be detected. Since temperature itself does not allow too many conclusions on the process, the distribution of the different elements within the furnace has to be considered. The various percentage amounts over time are represented in Table 25.

Table 25: Chemical composition of important elements in the second trial

Sample [Nr.]	Time [min]	C [%]	Si [%]	Mn [%]	Cu [%]	Zn [%]	Pb [%]
1	62	1.8800	0.0000	0.0900	0.0150	0.0023	0.0000
2	89	2.7200	0.0000	0.1600	0.0160	0.0110	0.0000
3	136	3.4900	0.0021	0.2310	0.0180	0.0013	0.0000
4	155	3.0400	0.0000	0.1420	0.0430	0.0042	0.0000
5	192	2.7400	0.0000	0.0910	0.0710	0.0071	0.0000
6	214	2.2700	0.0000	0.1200	0.1030	0.0056	0.0000
7	245	2.0400	0.0000	0.1630	0.1110	0.0030	0.0000

Unlike in the first trial, the carbon content does not vanish totally. It falls below the desired limit of 2.06 % after approximately 210 minutes, however, the reaction may already have been finished at this point. Having divided the addition of carbon in different steps, the first adding step clearly has an effect exactly one hour after the experiment's beginning. Throughout the reduction process the C content decreases almost linearly as can be seen from minute 110 to 200 in Figure 27. Following the same rules as before, silicon and the majority of manganese enter the slag phase. Copper on the contrary moves from the oxidic shape in the Waelz slag to the molten iron bath. Table 26 provides the actual composition of the regulus obtained after tapping.

Table 26: Chemical composition of the Fe regulus from the second trial

Element	Fe	C	Mn	P	S	Cr	Ni	Mo	Al	Cu
[%]	99.6060	0.0210	0.0230	0.0110	0.0530	0.0063	0.0330	0.0072	0.0033	0.1630

Following the same pattern as in the first trial, the mass balance constitutes the next important step. Once again, the weights that had been determined before, during and after the experiment realization are listed and compared. The input data on the one hand and the mass of the output on the other can be observed in the Sankey diagram in Figure 28.

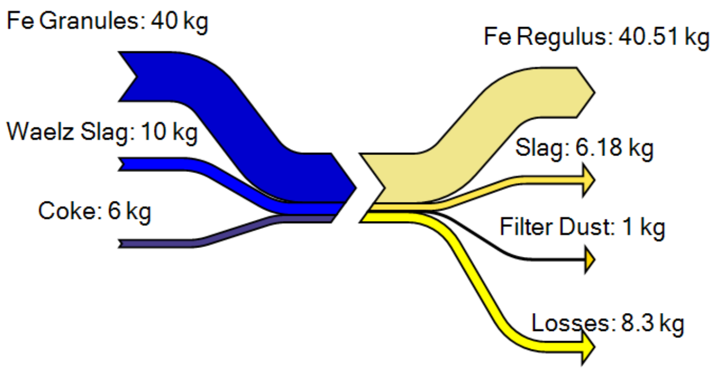

Figure 28: Mass balance from the second trial

In comparison to the first trial, the mass balance in Figure 28 shows a bigger difference in the sums of the input and output material. One modified parameter is presented by the fact that in the second trial no quartz sand was used. Keeping in mind that in this experiment 6 kg of coke were used gives an explanation for the majority of the missing material, however, the remaining C inside the regulus must be considered as well. By completely subtracting the coke from the input compounds only 2.3 kg of the material end up missing. On the one hand the inaccurate measurement of the filter dust may explain a part of this result, on the other errors during the sampling processes cannot be excluded. In contrast to the mass balance in the experiment before, the slag contains significantly less iron, hence providing a better separation of the two phases. In order to complete the investigation of the second trial, the slag is analysed as well. Table 27 states the total percentage of the different elements contained in the end slag of this experiment.

Table 27: Chemical slag composition from the second trial

Component	[%]
Fe	19.00
Pb	0.003
Zn	0.06
Al_2O_3	4.06
CaO	19.30
MgO	20.40
MnO	7.45
SiO_2	20.00
Fe_{met}	1.60

The most interesting difference compared to the first trial is represented by the considerably lower amount of Fe, whereas the obtained CaO/SiO_2-ratio of 0.97 demonstrates an almost neutral basicity. The percentage of these two compounds is also at higher levels, as can be seen in Figure 29.

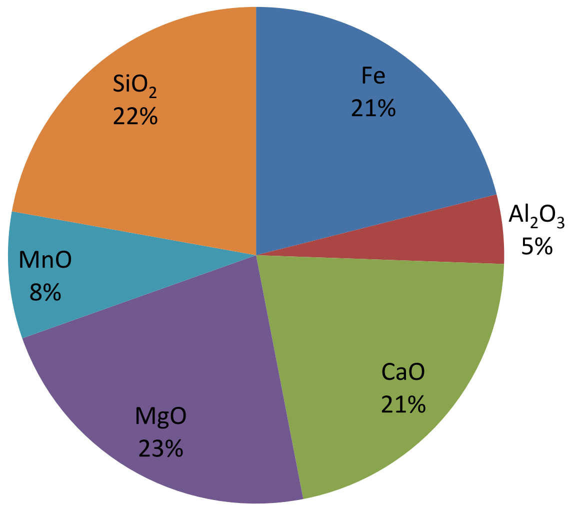

Figure 29: Chemical slag composition from the second trial

8.3 Results from Trial III

The analysis of the third experiment is performed in the same way as the two before. The temperature measurements using the external lance at different times are highlighted in Table 28.

Table 28: Sample, time and temperature from the third trial

Sample [Nr.]	Time [min]	Temperature [°C]
-	0	1551
1	46	1511
2	83	1512
3	116	1463
4	136	1437
5	152	1467
6	167	1468

Figure 30 depicts the on-line temperature recorded by the thermocouple inside the top blown rotary converter as well as the ϑ values taken with the lance and the distribution of the different elements within the trial.

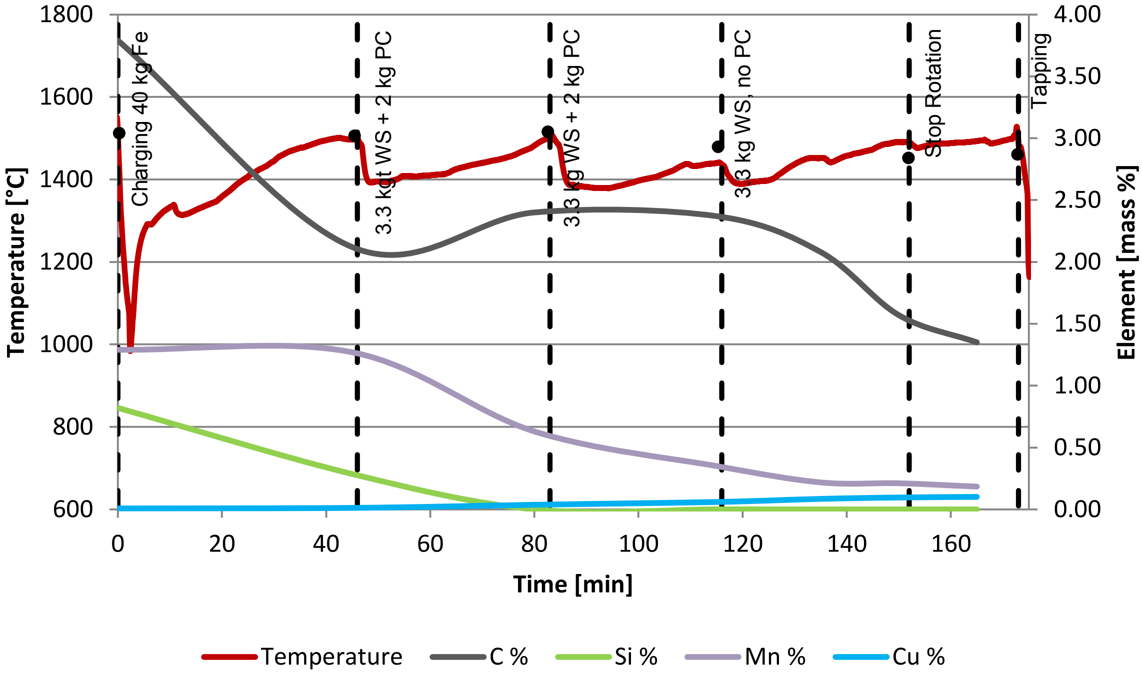

Figure 30: Measurements during the third trial

The temperature is kept quite stable with drops when charging the furnace with material. As shown in the figure, no carbon is fed into the furnace before charging the TBRC with Waelz slag this time. Another interesting aspect is represented by the fact of using petrol coke in contrast to the higher quality coke breeze used in the two trials before. Table 29 demonstrates the distribution of the different elements at various times in the process as already shown in Figure 30.

Table 29: Chemical composition of important elements in the third trial

Sample [Nr.]	Time [min]	C [%]	Si [%]	Mn [%]	Cu [%]	Zn [%]	Pb [%]
-	0	3.7900	0.8200	1.2900	0.0078	0.0019	0.0020
1	46	2.1200	0.2860	1.2700	0.0120	0.0037	0.0046
2	83	2.4000	0.0000	0.6300	0.0370	0.0130	0.0030
3	116	2.3700	0.0000	0.3500	0.0600	0.0057	0.0000
4	136	2.0800	0.0000	0.2180	0.0850	0.0075	0.0022
5	152	1.5700	0.0000	0.2110	0.0960	0.0017	0.0033
6	167	1.3500	0.0000	0.1840	0.1010	0.0067	0.0000

The results in the diagram can be compared to the ones in the second trial. An interesting difference is represented by the speed by which the carbon is consumed in the process.

While the consuming rate straight after feeding the converter with pig iron granules reaches approximately the same level as in the former experiment, it decreases a lot slower when being fed with petrol coke. The C level throughout the main process almost stays at the same level and has a value above 2.06 % which is necessary for the described reasons. On the opposite the reduction speed drops. Manganese is not fully transferred to the slag, whereas silicon needs more time to leave the metal phase as well. The chemical composition of the iron regulus at the end of the experiment is shown in Table 30.

Table 30: Chemical composition of the Fe regulus from the third trial

Element	Fe	C	Mn	P	S	Cr	Ni	Mo	Al	Cu
[%]	98.3000	1.2200	0.1440	0.0094	0.0990	0.0470	0.0180	0.0045	0.0020	0.0940

Due to the elevated remaining carbon and manganese content in the regulus, the percentage of iron is lower than in the two reguli before. The mass balance which is presented in the Sankey diagram in Figure 31 once again shows the weight difference between the input and output materials.

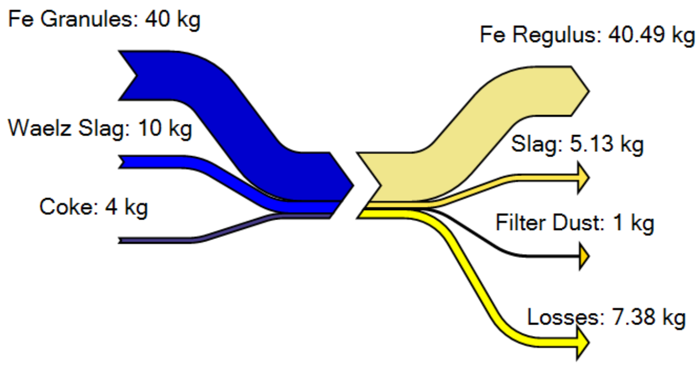

Figure 31: Mass balance from the third trial

Like in the trial before, no additional quartz sand was used this time. The two different sums from the input and output show an even bigger gap compared to the second experiment. By considering the consumption of the petrol coke, there are still more than 3 kg missing which can again be explained by iron and slag losses as well as tapping errors during the process. Despite these losses, the rather low weight of the slag constitutes a positive aspect when looking at the results. For further analysis, the slag has to be investigated which is done in Table 31.

Table 31: Chemical slag composition from the third trial

Component	[%]
Fe	21.80
Pb	0.009
Zn	0.05
Al_2O_3	3.92
CaO	22.00
MgO	14.80
MnO	9.29
SiO_2	19.50
Fe_{met}	3.87

The slag's chemical composition is quite similar to the one in the second trial. While the iron content is kept at lower levels, CaO, SiO_2 and MgO play an important role and lead to the even less acid basicity of 1.13 in this process. Figure 32 graphically shows the distribution of the slag components in relation to each other.

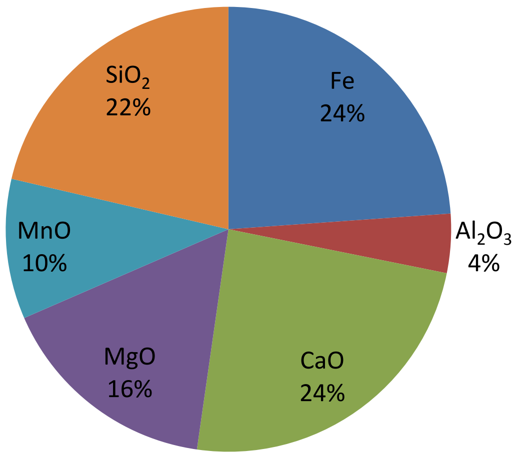

Figure 32: Chemical slag composition from the third trial

9 Economic Part

This part of the thesis deals with the economic aspects of the technology for recycling Waelz slag that has been presented in the previous chapters. Therefore, a brief overview of the process parameters is given which is followed by a detailed description and calculation of the capital expenditure (CAPEX) as well as the operational expenditure (OPEX). In order to achieve a significant statement for the profitability of the new process throughout the project period, the discounted cash flow method is used to compare the costs and earnings and present the net present value.

9.1 General Aspects

Since a project of this kind has never been executed before, there are some uncertainty factors within the parameters. This is the reason why, beside a calculation with realistic values taken from the industry, scenarios symbolizing the best as well as the worst case are additionally performed.

In total, the project is supposed to be executed over a lifespan of 20 years, for which reason all assumptions regarding costs such as depreciation relate to this time. All monetary aspects are calculated in USD due to their universal adaptability and comparability. The volatile exchange rate from EUR to USD constitutes a highly important factor. Since the value constantly fluctuates, the current value of 1.38 USD per EUR from the 8th of May 2014 constitutes the basis for the calculations in order to make the results consistent and comparable. However, this number can be varied within the composed and presented Excel file anytime. Inflation is considered as an influential parameter as it plays a significant factor because of the project's life span of 20 years. It demonstrates an important role in the calculation of the earnings and the operational expenditure and is given a value of 2 %. Therefore, all financial amounts constitute so called nominal numbers, not real ones. All other assumptions and details regarding costs will be mentioned in the following chapters.

9.2 Initial Situation

Similar to the determination of the technological aspects, all economic numbers are calculated in the same Excel file. In order to clarify the initial situation and state all important input factors, these are highlighted and modifiable throughout the calculations. Table 32 shows the most important parameters. While the colour yellow emphasizes the opportunity to change the factor, red fields illustrate calculated values.

Table 32: Input parameters for the economic calculation

400	°C Input Temperature		
1'500	°C Reaction Temperature		
70'000'000	kg Waelz Slag		
140'000'000	kg Iron Bath	Ratio 1:	2
34'500'000	kg Carbon	Ratio 10:	3.5
-	kg Additives		
197'584'641	MJ Total Energy needed		
6'898'554	Nm³ CH_4 needed		

The input temperature can be chosen between values of 20 °C and 600 °C. Latter one means a direct charging from the Waelz tube and hence savings of heating costs and carbon input. The reaction temperature is set to a number of 1500 °C throughout the calculations because the ϑ in the experiments was about the same, however, it may be varied upon further notice. Befesa states that approximately 70.000 t of Waelz slag accumulate throughout the year which is why this value is chosen. Keeping a ratio of 1:2 for the Waelz slag compared to the iron bath, this means around 140.000 t of pig iron required throughout the year. In fact, the liquid iron bath can be used continuously, so there is only need for the first charge of around 5 t which represents a negligible value compared to the other numbers. Like the input temperature, this ratio may be varied as well. However, by using double the amount of iron bath compared to the Waelz slag, a thorough reaction should be guaranteed. The same thoughts apply for the use of carbon, even though in this case a variation has a more significant impact on the operating costs. The trials from the top blown rotary converter have shown that a stoichiometric amount of C does not lead to the desired reduction. Only at the ratio of around 10:3.5 a satisfying result could be achieved. By modifying the process and considering the reduction conditions, the amount of needed coke can be lowered. Regarding the additives such as lime or quartz sand, none were used, however, the program offers the opportunity to enter any so they too will be considered in the cost evaluation.

Based on the calculations from the mass balance and the specific energy delivered by the burner gases, the necessary amount of energy for the reduction of the different oxides is determined. Subsequently, the total CH_4 needed for this process is delivered. The required energy for warming the first batch as well as the amount for heating the converter when not in operation is not integrated in this number, however, appropriate effectiveness factors are considered in the corresponding chapters.

9.3 Capital Expenditure

The first step of investigating the cost structure of this new project is the one of developing a model for the capital expenditure. Here, some important factors are considered and like described earlier, a best as well as a worst case scenario are presented too. For calculating these two variations, a certain percentage of expenditure is added or subtracted. In the best case scenario the average costs for facilities such as land or building and input materials are at 80 % compared to the realistic case, whereas in the worst case the percentage rises to a number of 120 %. These values represent assumptions and can easily be altered in the file. In order to arrive at the total capital expenditure, the different factors have to be split and to be looked upon separately. A separate chapter at the end deals with the important topic of the depreciation time.

9.3.1 Land

The area necessary for building any further installations constitutes the first step of the CAPEX determination. First, a calculation using actual and current numbers from the metallurgical industry is performed and in a second step the same procedure takes place for the best and the worst case scenario.

9.3.1.1 Land Costs Realistic Case

A total amount of 2.000 m² is suggested for the planned project. There is sufficient space for a hall, the important reaction vessels as well as for any further installations. Using the price given in Table 33 an overall sum of 331.200 USD constitutes the result.

Table 33: Hall costs for the realistic case

Size needed	2'000	m²
EUR/m²	120.0	EUR/m²
USD/m²	165.6	USD/m²
Price	331'200	USD

9.3.1.2 Land Costs Best Case

For the best case, the total area that is needed for the different facilities reaches a value of 1.800 m². This can on the one hand be argued by the fact that constructions such as a hopper or a silo may be arranged more efficiently and on the other with the reason that they might not even be necessary. In total, the costs for land decrease from 331.200 USD to 238.464 USD compared to the realistic case as Table 34 describes.

Table 34: Hall costs for the best case

Size needed	1'800	m²
EUR/m²	96.0	EUR/m²
USD/m²	132.5	USD/m²
Price	238'464	USD

9.3.1.3 Land Costs Worst Case

In contrast to the best case, the costs for land increase by a percentage of 20 %. Additionally, an area of 2.200 m² is suggested for the different facilities. Therefore, the total price for land rises to a sum of 437.184 USD like the calculation in Table 35 shows.

Table 35: Hall costs for the worst case

Size needed	2'200	m²
EUR/m²	144.0	EUR/m²
USD/m²	198.7	USD/m²
Price	437'184	USD

9.3.2 Building

For the building the same assumptions as for the land apply. Beside the calculation using real numbers from comparable industrial projects, a best case and a worst case scenario are suggested as well.

9.3.2.1 Building Costs Realistic Case

By considering all further facilities such as the reduction vessels, the exhaust system and possible hoppers and mixers, a total hall area of 1.500 m² serves best for protecting the equipment from any weather conditions. Since input as well as output materials appear in large quantities, a crane will be necessary in order to manoeuvre all of them safely. After adding the different costs, Table 36 states a total price of 620.850 USD for the building.

Table 36: Building costs for the realistic case

Size needed	1'500	m²
EUR/m²	155.0	EUR/m²
USD/m²	213.9	USD/m²
Crane	300'000	USD
Price	620'850	USD

9.3.2.2 Building Costs Best Case

The assumption of lowering the area needed for the different facilities is copied from the land costs in this case. Therefore, 1.400 m² serve as building area for the best case and implicate a value of 479.568 USD as calculated in Table 37.

Table 37: Building costs for the best case

Size needed	1'400	m²
EUR/m²	124.0	EUR/m²
USD/m²	171.1	USD/m²
Crane	240'000	USD
Price	479'568	USD

9.3.2.3 Building Costs Worst Case

Compared to the realistic case, the costs per square meter as well as for the crane are by 20 % higher, whereas the required area increases by 100 m². Hence, Table 38 depicts that the overall expense rises to a number of 770.688 USD.

Table 38: Building costs for the worst case

Size needed	1'600	m²
EUR/m²	186.0	EUR/m²
USD/m²	256.7	USD/m²
Crane	360'000	USD
Price	770'688	USD

9.3.3 Top Blown Rotary Converter

Since the TBRC is the actual reaction vessel, it constitutes the heart of the new recycling process for Waelz slag. The presented model is based on an offer by Andritz Metals and includes all accessories such as a CH_4 burner and the installation that are needed for a fully functioning furnace.

9.3.3.1 Top Blown Rotary Converter Costs Realistic Case

As 70.000 t of Waelz slag constitute a big amount of treatable material and an average TBRC offers space for approximately 9 t, a total number of two seems to solve the question of necessary furnaces. Assuming a full filling weight, this leads to a total of 7.778 charges throughout a year and consequently 3.889 per top blown rotary converter. However, since the process is run continuously, any statements regarding charging and shift plans cannot be generalized. Table 39 delivers total costs of 16.284.000 USD for the two TBRCs.

Table 39: Top blown rotary converter costs for the realistic case

WS amount	70'000	t/year
Size	9	t
Amount TBRC	2	Units
EUR/TBRC	5'900'000	EUR/TBRC
USD/TBRC	8'142'000	USD/TBRC
Price	16'284'000	USD

9.3.3.2 Top Blown Rotary Converter Costs Best Case

Whereas the amount of necessary furnaces remains the same, the costs for each converter are assumed to decrease by 20 % compared to the realistic case. Hence, the calculation in Table 40 leads to a calculated expenditure of 13.027.200 USD.

Table 40: Top blown rotary converter costs for the best case

WS amount	70'000	t/year
Size	9	t
Amount TBRC	2	Units
EUR/TBRC	4'720'000	EUR/TBRC
USD/TBRC	6'513'600	USD/TBRC
Price	13'027'200	USD

9.3.3.3 Top Blown Rotary Converter Costs Worst Case

The only difference from the best case is the fact that instead of subtracting the additional 20 % they are added to the original sum. Table 41 shows an increased overall amount of 19.540.800 USD for the worst case scenario.

Table 41: Top blown rotary converter costs for the worst case

WS amount	70'000	t/year
Size	9	t
Amount TBRC	2	Units
EUR/TBRC	7'080'000	EUR/TBRC
USD/TBRC	9'770'400	USD/TBRC
Price	19'540'800	USD

9.3.4 Hopper

Hoppers are needed for the storage of optional additives such as lime or quartz sand. Since these materials may vary in composition as well as in quantity, two storage tanks are assumed to serve as reserve. Ideally, the Waelz slag is fed into the converter straight after being collected from the Waelz kiln for which reason no need for an additional hopper arises. Since the coke breeze's behaviour can be compared to dust, it is stored in boxes for transportation.

9.3.4.1 Hopper Costs Realistic Case

A hopper with an adequate size will measure around 20 m² and will offer space for approximately 100 t of additives, depending on the bulk density of the respective material. As described, two hoppers provide enough reserve for possible additive materials. Table 42 gives more details of the different parameters and calculates a total price of 173.880 USD for the two tanks.

Table 42: Hopper costs for the realistic case

Area	20	m²
Size	120	m³
Capacity	100	t
EUR/Hopper	63'000	EUR/Unit
USD/Hopper	86'940	USD/Unit
Number of Hoppers	2	Units
Price	173'880	USD

9.3.4.2 Hopper Costs Best Case

The area that will be needed as well as the provided capacity for the two hoppers is the same as in the realistic case. The only difference is the price of the tanks that decreases by a percentage of 20 % which leads to a sum of 139.104 USD as Table 43 states.

Table 43: Hopper costs for the best case

Area	20	m²
Size	120	m³
Capacity	100	t
EUR/Hopper	50'400	EUR/Unit
USD/Hopper	69'552	USD/Unit
Number of Hoppers	2	Units
Price	139'104	USD

9.3.4.3 Hopper Costs Worst Case

Instead of reducing the price per unit, it is raised by 20 % compared to the realistic case. Therefore, the total expense increases by the same amount. Table 44 demonstrates the total costs of 208.656 USD.

Table 44: Hopper costs for the worst case

Area	20	m²
Size	120	m³
Capacity	100	t
EUR/Hopper	75'600	EUR/Unit
USD/Hopper	104'328	USD/Unit
Number of Hoppers	2	Units
Price	208'656	USD

9.3.5 Mixer

Since there is constant movement within the top blown rotary converter, the question arises if a mixer is necessary in order to guarantee an almost homogenous distribution of the different input materials. Therefore, different solutions are presented for the three scenarios.

9.3.5.1 Mixer Costs Realistic Case

In the realistic case scenario no mixer has to be acquired due to the described guaranteed movement within the furnace and the resulting homogenization. Thus, no additional costs arise as Table 45 confirms.

Table 45: Mixer costs for the realistic case

Area	50	m²
Capacity	100	t
EUR/Mixer	250'000	EUR/Unit
USD/Mixer	345'000	USD/Unit
Number of Mixers	-	Units
Price	-	USD

9.3.5.2 Mixer Costs Best Case

The costs of the mentioned device drop by 20 %, however, like in the realistic case, this scenario also does not include a mixer which is why no further costs occur as can be seen in Table 46.

Table 46: Mixer costs for the best case

Area	50	m²
Capacity	100	t
EUR/Mixer	200'000	EUR/Unit
USD/Mixer	276'000	USD/Unit
Number of Mixers	-	Units
Price	-	USD

9.3.5.3 Mixer Costs Worst Case

In contrast to the two scenarios mentioned before, the worst case requires a mixer. Here, the TBRC does not guarantee sufficient mixing of the raw materials, so the best possible conditions for a full reaction are not achieved. By also increasing the price per unit by 20 %, Table 47 shows a total amount of 414.000 USD.

Table 47: Mixer costs for the worst case

Area	50	m²
Capacity	100	t
EUR/Mixer	300'000	EUR/Unit
USD/Mixer	414'000	USD/Unit
Number of Mixers	1	Units
Price	414'000	USD

9.3.6 Exhaust System

The exhaust system deals with the off gas and provides compliance with standards regarding the environment. Here the question arises if the capacity that is already installed in the plant due to the recycling of electric arc furnace dust using Waelz furnaces is sufficient to deal with the off gas from an additional process. In each of the three presented scenarios an additional exhaust system is necessary.

9.3.6.1 Exhaust System Costs Realistic Case

By considering values from the metallurgical industry, an adequate exhaust system is available at prices starting from 260.000 EUR or 358.800 USD. Additional services, such as installation and build-up, are included in this amount.

9.3.6.2 Exhaust System Costs Best Case

The only difference compared to the realistic case is the fact that the costs for the exhaust system decrease by the factor of 20 %. Hence, the final price for the whole setup is at 240.000 EUR or 331.200 USD.

9.3.6.3 Exhaust System Costs Worst Case

Instead of subtracting the 20 % from the original amount, the same percentage is added to the original price. The overall value of the exhaust system sums up to 280.000 EUR or 386.400 USD in the worst case scenario.

9.3.7 Groundwork

Groundwork marks the area that is prepared in order to stabilize the ground and hence make it safe for operational processes. Area for equipment such as the top blown rotary converters or transport routes are subject to this type of treatment.

9.3.7.1 Groundwork Costs Realistic Case

When looking at the area that is necessary for the TBRCs and the hopper as well as optional additional mixers, a total of 500 m² should prove to offer sufficient space. Table 48 shows the numbers for the general price calculation of groundwork.

Table 48: Groundwork costs for the realistic case

Area	500	m²
EUR/m²	95.0	EUR/m²
USD/m²	131.1	USD/m²
Price	65'550	USD

9.3.7.2 Groundwork Costs Best Case

The necessary area remains the same for the best case scenario because the equipment and the transport routes are identical to the ones presented earlier. By lowering the price per m² by 20 %, the total amount adds up to 52.440 USD as can be seen in Table 49.

Table 49: Groundwork costs for the best case

Area	500	m²
EUR/m²	76.0	EUR/m²
USD/m²	104.9	USD/m²
Price	52'440	USD

9.3.7.3 Groundwork Costs Worst Case

Once again, the only aspect that differs from the best case scenario is the addition of 20 % of the costs instead of subtracting them. Table 50 depicts the needed area of 500 m² and the overall price of 78.660 USD for the groundwork.

Table 50: Groundwork costs for the worst case

Area	500	m²
EUR/m²	114.0	EUR/m²
USD/m²	157.3	USD/m²
Price	78'660	USD

9.3.8 Buffer Space

The buffer space constitutes an area which offers the opportunity to perform miscellaneous tasks such as storing materials momentarily or doing repair work. In general, it is a non-built-up zone in order to guarantee free space if it is needed.

9.3.8.1 Buffer Space Costs Realistic Case

The realistic case suggests a total area of 100 m². This paved zone offers the chance to perform any necessary tasks and does not have a big influence on the capital expenditure with an amount of 9.660 USD as Table 51 demonstrates.

Table 51: Buffer space costs for the realistic case

Area	100	m²
EUR/m²	70.0	EUR/m²
USD/m²	97.0	USD/m²
Price	9'660	USD

9.3.8.2 Buffer Space Costs Best Case

When looking at the best case scenario, no extra buffer space is needed for the project. All facilities are assumed to combine perfectly. As a result, Table 52 states that no additional costs appear.

Table 52: Buffer space costs for the best case

Area	-	m²
EUR/m²	56.0	EUR/m²
USD/m²	77.3	USD/m²
Price	-	USD

9.3.8.3 Buffer Space Costs Worst Case

In contrast to the best case, the worst case scenario is not based on the same assumptions when looking at the combination of the different facilities. Hence, double the space will be needed for additional storing or repair work. As the price per m² also increases by 20 %, Table 53 leads to the total sum of 23.184 USD for the buffer space.

Table 53: Buffer space costs for the worst case

Area	200	m²
EUR/m²	84.0	EUR/m²
USD/m²	115.9	USD/m²
Price	23'184	USD

9.3.9 Total CAPEX

Since all important parameters for the capital expenditure have been mentioned and explained, an addition of the various factors constitutes the next step. Here, the different prices are summed up and contingency costs are added at various percentage rates, depending on the scenario. Since the new recycling concept is based on a certain infrastructure that already exists at Befesa, further factors that have not been mentioned such as office buildings, roads and a parking area are not included. An important thing to consider is the fact that the shown values only represent the correct result when performing the calculations with the data provided in each chapter. By varying input parameters such as the EUR/USD exchange rate or a different m² price, another CAPEX sum will originate.

9.3.9.1 Total CAPEX Realistic Case

By considering the eight different cost drivers land, building, TBRCs, hopper, mixer, exhaust system, groundwork as well as buffer space and using the data explained in the general aspects, an overall CAPEX of 17.843.940 USD provides the result. Figure 33 impressively demonstrates the impact of the main cost driver TBRC on the capital expenditure compared to the other components. However, since a project of this kind has never been performed before, certain contingency costs have to be added. By comparing the new concepts with other ones, a percentage of 20 % for the realistic case guarantees calculations on the safe side and prevents disappointment and unforeseen future costs. After integrating this amount, 21.412.728 USD represent the total capital expenditure for the new recycling concept of Waelz slag.

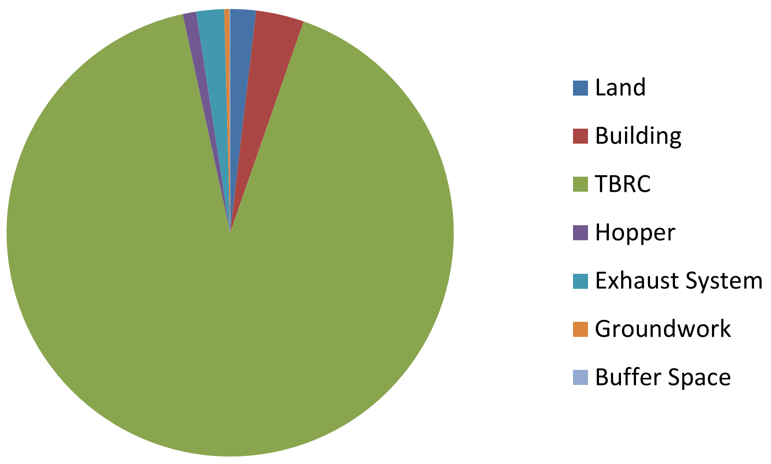

Figure 33: Distribution of the CAPEX cost drivers

9.3.9.2 Total CAPEX Best Case

Adding the different costs from the best case scenarios expectedly lead to a lower CAPEX with 14.267.976 USD. By assuming a lower contingency rate of 15 % and adding it to the actual number, a total amount of 16.408.172 USD represents the result, hence showing a value lower by more than 5 million USD compared to the realistic case.

9.3.9.3 Total CAPEX Worst Case

In contrast to the best case, this scenario deals with the different expenses representing the worst conditions. By adding higher contingency costs with a rate of 25 % to the calculated CAPEX of 21.859.572 USD, the total capital expenditure for this assumption lies at a value of 27.324.465 USD and shows a big difference compared to the realistic case.

9.3.10 Depreciation

Since depreciation time and costs play highly important factors in a financing decision, some aspects regarding these topics are presented in this chapter. An emphasis has to be put on the fact that all decisions are based on comparable data from the industry, however, there is a big uncertainty as there has never been a similar project before. Table 54 gives an overview over the depreciation time of the different cost drivers.

Table 54: Depreciation time of the different cost drivers

Land	40	years
Building	40	years
TBRC	20	years
Hopper	20	years
Mixer	20	years
Exhaust System	20	years
Groundwork	40	years
Buffer Space	40	years

Usually the depreciation time for industrial acquirements takes between 10-20 years. Since the new recycling concept shows a project life span of 20 years, all machines and facilities are expected to endure this amount of time when putting a special focus on maintenance. Therefore, no new investments would be necessary for equipment such as the top blown rotary converters during the project’s life time. Table 55 displays the different depreciation costs by expressing the terminal values for the mentioned items for the realistic case as well as for the best and the worst case scenario after 20 years.

Table 55: Terminal values for the depreciation

Item	Terminal Value	Realistic Case	Best Case	Worst Case	Unit
Land	100 %	331'200	238'464	437'184	USD
Building	50 %	310'425	239'784	385'344	USD
TBRC	0 %	-	-	-	USD
Hopper	0 %	-	-	-	USD
Mixer	0 %	-	-	-	USD
Exhaust System	0 %	-	-	-	USD
Groundwork	50 %	65'550	26'220	39'330	USD
Buffer Space	50 %	4'830	-	11'592	USD
End of Project Sum	-	712'005	504'468	873'450	USD

Land is expected to keep its value for which reason there is no decrease after 20 years when looked at the numbers in Table 55. In contrast, the building is assumed to lose its value after 40 years which is why after the project’s life span it still possesses half of the starting price. Maintenance intense facilities such as the TBRC, the mixer or the exhaust system and the hoppers are totally depreciated over the 20 years. This value signifies a long time, however, corresponding maintenance costs will be added in the concerning operational expenditure part. For the groundwork as well as for the buffer space the same assumptions as for the building apply. At the end, the sum of the different parameters can be calculated. In the realistic case all facilities show a total terminal value of 712.005 USD, whereas the best case leads to an amount of 504.468 USD and the worst case to 873.450 USD. The high number of latter one can be explained by the large investment costs when starting off the project.

9.4 Operational Expenditure

For the OPEX the same rules as for the capital expenditure apply. All operational parameters are first described and calculated with values that can be compared with industrial standards and in an additional part a best and a worst case scenario are presented. For these, a decrease or an increase of the costs signify the most important parameter, however, some other modifications are offered as well. At the end of the chapter, the overall operational costs are presented and compared among each other.

9.4.1 Raw Materials

The raw materials constitute the most important input parameter for a successful recycling process. Altogether 70.000 t of Waelz slag will accumulate every year for which reason the process is designed for this amount. Since the slag has been sent to landfill and a fee of 20 EUR per ton had to be paid up to now, this raw material represents a free source. Additionally, the fee will be added to the income, a fact which is presented in the chapter regarding earnings.

9.4.1.1 Raw Material Costs Realistic Case

As the Waelz slag does not play a factor in the calculation of the raw materials, the main cost driver is transferred to the coke. Table 56 confirms this detail. When aiming at a slag to coke ratio of 10:3.5, a total of 24.500 t coke will be needed every year. This value represents approximately 2.5 the stoichiometric amount that is required for a theoretical reduction. The trials in the practical part have shown that an exceeded ratio is necessary, however, these experiments have only been performed on laboratory scale. Since carbon is one of the most significant cost drivers beside the reaction temperature, ideal conditions will have to be adjusted when operating at a bigger scale. Starting points are the right carbon to burner gas ratio when charging the materials as well as an elaborated feeding scheme. For the Waelz slag to carbon proportion of 10:3.5 and the industrial price of 130 EUR per ton of this raw material, annual costs of 4.395.300 USD arise.

Pig iron does not play an important role in the calculation of the raw materials as it is only needed for the first charging of the two converters. An amount of 10 t per year only increases the raw material costs by a total of 3.450 USD. Since for the start-up of the process no additives such as lime or quartz sand are contemplated, these factors do not influence the price at all. However, the option to add any additional material later on still exists which is why they are not completely excluded from the list. By considering a total input weight of 94.510 t every year – a number which will have an influence on the internal transport costs –

the raw material price reaches a sum of 4.398.750 USD as the penultimate line in Table 56 displays.

Table 56: Raw material costs for the realistic case

Waelz Slag	70'000	t/year
EUR/t	-	EUR/t
USD/t	-	USD/t
Total Costs	-	USD/year
Coke	24'500	t/year
EUR/t	130.0	EUR/t
USD/t	179.4	USD/t
Total Costs	4'395'300	USD/year
Pig Iron	10	t/year
EUR/t	250.0	EUR/t
USD/t	345.0	USD/t
Total Costs	3'450	USD/year
Additives		
Sand	-	t/year
EUR/t	10.0	EUR/t
USD/t	13.8	USD/t
Lime	-	t/year
EUR/t	110.0	EUR/t
USD/t	152.0	USD/t
Total Costs	-	USD/year
Total Raw Materials	4'398'750	USD/year
Sum Weight	94'510	t/year

9.4.1.2 Raw Material Costs Best Case

Since the amount of accumulated Waelz slag represents a given value by Befesa, it is not varied for the best case scenario. The coke price drops to an average industrial minimal value of 110 EUR/t and results in an overall expense of 3.719.100 USD per year. As the pig iron does not play an important role, its reduced price does not influence the result significantly. The total raw materials costs sum up to 3.721.860 USD for this case as can be seen in Table 57.

Table 57: Raw material costs for the best case

Waelz Slag	70'000	t/year
EUR/t	-	EUR/t
USD/t	-	USD/t
Total Costs	-	USD/year
Coke	24'500	t/year
EUR/t	110.0	EUR/t
USD/t	151.8	USD/t
Total Costs	3'719'100	USD/year
Pig Iron	10	t/year
EUR/t	200.0	EUR/t
USD/t	276.0	USD/t
Total Costs	2'760	USD/year
Additives		
Sand	-	t/year
EUR/t	8.0	EUR/t
USD/t	11.0	USD/t
Lime	-	t/year
EUR/t	88.0	EUR/t
USD/t	121.4	USD/t
Total Costs	-	USD/year
Total Raw Materials	3'721'860	USD/year
Sum Weight	94'510	t/year

9.4.1.3 Raw Material Costs Worst Case

The only big difference in the worst case scenario is the coke price that rises from the average 130 EUR to the industrial maximum of 140 EUR per ton. By considering the total costs of 4.733.400 USD for this raw material and adding the raised amount of 4.140 USD for the pig iron, overall costs of 4.734.540 incur. The breakdown of the different parameters can be seen in Table 58.

Table 58: Raw material costs for the worst case

Waelz Slag	70'000	t/year
EUR/t	-	EUR/t
USD/t	-	USD/t
Total Costs	-	USD/year
Coke	24'500	t/year
EUR/t	140.0	EUR/t
USD/t	193.2	USD/t
Total Costs	4'733'400	USD/year
Pig Iron	10	t/year
EUR/t	300.0	EUR/t
USD/t	414.0	USD/t
Total Costs	4'140	USD/year
Additives		
Sand	-	t/year
EUR/t	12.0	EUR/t
USD/t	16.6	USD/t
Lime	-	t/year
EUR/t	132.0	EUR/t
USD/t	182.2	USD/t
Total Costs	-	USD/year
Total Raw Materials	4'734'540	USD/year
Sum Weight	94'510	t/year

9.4.2 Refractory Material

The refractory material for the top blown rotary converter also plays a part in the calculation of the operational expenditure. Since its quality decreases over the life time due to wear, it has to be renewed at a certain point. Depending on the case looked upon, this procedure has to be performed between 1-3 times every year. The refractories inside the TBRCs for the Waelz slag recycling process are of a mag-chrome type and will be supplied by the Austrian corporation RHI AG.

9.4.2.1 Refractory Material Costs Realistic Case

When compared to the performed tests at the University of Leoben, a renewal of the converters' lining should happen twice a year. Consequently, the vessels' refractory material would always guarantee ideal reaction conditions for the reduction process on the one hand and a safe operation mode on the other. RHI states a price of 56.000 EUR or 77.280 USD per lining, hence the overall costs for the refractories mount up to 309.120 USD every year, a number which can also be observed in Table 59.

Table 59: Refractory material costs for the realistic case

Amount TBRC	2	Units
Linings	2	Linings/year
EUR/lining	56'000	EUR/lining
USD/lining	77'280	USD/lining
Total Refractories Costs	309'120	USD/year

9.4.2.2 Refractory Material Costs Best Case

When assuming a higher resistance against wear and corrosion, a longer refractory life time can be achievable. Depending on the actual process conditions, this could lead to just one renewal per converter every year in the best case scenario as Table 60 shows. Accordingly, this leads to a total amount of 123.648 USD every year. Further details will have to be investigated and samples will have to be taken during operation once the reaction vessels are in operation.

Table 60: Refractory material costs for the best case

Amount TBRC	2	Units
Linings	1	Linings/year
EUR/lining	44'800	EUR/lining
USD/lining	61'824	USD/lining
Total Refractories Costs	123'648	USD/year

9.4.2.3 Refractory Material Costs Worst Case

In contrast to the preceding scenario, worse wear and corrosion conditions are predicted for this case. Therefore, three linings for each converter are assumed every year for which reason the total refractory costs increase significantly compared to the realistic situation. Table 61 delivers a price of 556.416 USD/year.

Table 61: Refractory material costs for the worst case

Amount TBRC	2	Units
Linings	3	Linings/year
EUR/lining	67'200	EUR/lining
USD/lining	92'736	USD/lining
Total Refractories Costs	556'416	USD/year

9.4.3 Burner Gases

Beside the raw materials, the burner gases are the other very important cost drivers in the new recycling concept. The most significant influencing factor is represented by the actual input temperature that is the ϑ at which the Waelz slag is charged into the top blown rotary converter. The limits are room temperature or 20 °C on the one end and 600 °C on the other, since this is the temperature the slag has got when exiting the Waelz kiln. The best possible solution would be to charge the slag directly from one vessel into the other as a lot of heating energy could be saved. For example, when comparing the amount of CH_4 that is required for reaching the reaction ϑ of 1500 °C, the difference can easily be demonstrated. If the slag is first cooled and then reheated from 25 °C in the process, a sum of 8.497.059 Nm³ of this burner gas is necessary, whereas a direct use after the Waelz kiln terminates in a value of 5.968.496 Nm³. This signifies an overall saving of 2.528.563 Nm³ CH_4 when using the preheated input material. By using the operational expenditure, this means a total amount of 3.446.565 USD every year. Therefore, the question regarding the best achievable input temperature can possibly decide the profitability of the whole project. If the Waelz slag is transported directly from the furnace to the TBRC, adequate containers should be provided.

Beside methane, oxygen plays a highly important role as well when regarding the combustion and hence the energy supply for the processes. The CH_4:O_2 ratio λ showed a value of 0.9 during the experiments at the University of Leoben and sets the basis for further calculations.

9.4.3.1 Burner Gas Costs Realistic Case

For the realistic case, an input temperature of the Waelz slag of 400 °C is chosen. This means the saving of the energy costs that would be necessary in order to heat the material from room temperature, however, not the full frame of 600 °C is exploited. By using the energy balance from the theoretical part, a total amount of 6.898.554 Nm³ CH_4 can be determined in Table 62. Since there are different kinds of losses in real processes, some are considered in this project too. On the one hand the heat transfer from the gases to the metal bath and the slag are presumed to have an efficiency of 80 %, hence the efficiency factor η_1 constitutes a value of 0.80. The refractory material absorbs some of the heat as well which leads to another η_2 of 0.95. These losses are not expected to be any higher due to the isolation of the refractories inside the TBRC. A third efficiency factor describes the gas amount that will be needed in order to keep the molten iron liquid when no slag is being charged. This will be the case during the nights as the process is most likely to run on a two shift model, a detail which will be described in the next chapter. As a reference, a little more than 10 % of the usual energy is expected to be necessary for this purpose which leads to another η of approximately 0.90.

By multiplying the needed amount of methane with the industrial price of 0.57 USD/Nm³ and dividing this product by the combination of the different efficiency factors, the total CH_4 costs of 5.706.435 USD can be determined. The step of applying a λ of 0.90 leads to the required oxygen sum of 6.208.698 Nm³. As O_2 is always used in combination with methane, the same efficiency factors are valid. Overall, a total of 2.129.475 USD is needed when using a price of 0.23 USD/Nm³ for oxygen.

Table 62: Burner gas costs for the realistic case

CH_4 needed	6'898'554	Nm³/year
EUR/Nm³	0.41	EUR/Nm³
USD/Nm³	0.57	USD/Nm³
Efficiency Factor η_1	0.80	-
Efficiency Factor η_2	0.95	-
Heating Overnight η_3	0.90	-
Total CH_4 Costs	5'706'435	USD/year
Lambda	0.90	-
O_2 needed	6'208'698	Nm³/year
EUR/Nm³	0.17	EUR/Nm³
USD/Nm³	0.23	USD/Nm³
Efficiency Factor η_1	0.80	-
Efficiency Factor η_2	0.95	-
Heating Overnight η_3	0.90	-
Total O_2 Costs	2'129'475	USD/year

9.4.3.2 Burner Gas Costs Best Case

Since the temperature influence of the Waelz slag has already been shown, the best case scenario does not broaden this topic and remains with different gas expenses as well as varying efficiency factors. The CH_4 as well as the O_2 prices decrease by 20 %, whereas the heat transfer is expected to improve to a factor of 0.85. By assuming almost no wall losses, η_2 can be raised to 0.98 while the overnight heating drops to a little more than 5 % and consequently shows a η of 0.95. These assumptions help to reduce the methane costs to a total of 3.945.866 USD/year. In the case of oxygen the same rules apply as for the other burner gas. By performing the calculations with an O_2 price of 0.19 USD/Nm³, overall costs of 1.472.482 USD/year are achieved for this gas component. Table 63 displays the breakdown of the mentioned factors.

Table 63: Burner gas costs for the best case

CH_4 needed	6'898'554	Nm³/year
EUR/Nm³	0.33	EUR/Nm³
USD/Nm³	0.45	USD/Nm³
Efficiency Factor η_1	0.85	-
Efficiency Factor η_2	0.98	-
Heating Overnight η_3	0.95	-
Total CH_4 Costs	3'945'866	USD/year
Lambda	0.90	-
O_2 needed	6'208'698	Nm³/year
EUR/Nm³	0.14	EUR/Nm³
USD/Nm³	0.19	USD/Nm³
Efficiency Factor η_1	0.85	-
Efficiency Factor η_2	0.98	-
Heating Overnight η_3	0.95	-
Total O_2 Costs	1'472'482	USD/year

9.4.3.3 Burner Gas Costs Worst Case

Table 64 provides identical information regarding the burner gas costs for the worst case scenario. Instead of lowering the gas prices, 20 % of the initial amount is added this time. In addition, the efficiency factors deteriorate. The heat transfer from the gas to the slag and the liquid iron bath drops to 0.75 while the losses increase and show a slightly lower value of 0.92. In order to keep the pig iron liquid overnight, an efficiency factor of 0.85 is assumed this time. In total, the CH_4 costs add up to 7.986.090 Nm³/year and the ones for O_2 to 2.980.175 Nm³/year for the worst case scenario.

Table 64: Burner gas costs for the worst case

CH_4 needed	6'898'554	Nm³/year
EUR/Nm³	0.49	EUR/Nm³
USD/Nm³	0.68	USD/Nm³
Efficiency Factor η_1	0.75	-
Efficiency Factor η_2	0.92	-
Heating Overnight η_3	0.85	-
Total CH_4 Costs	7'986'090	USD/year
Lambda	0.90	-
O_2 needed	6'208'698	Nm³/year
EUR/Nm³	0.20	EUR/Nm³
USD/Nm³	0.28	USD/Nm³
Efficiency Factor η_1	0.75	-
Efficiency Factor η_2	0.92	-
Heating Overnight η_3	0.85	-
Total O_2 Costs	2'980'175	USD/year

9.4.4 Labour and Maintenance

The creation of an adequate shift model for the operation of the TBRCs constitutes a main challenge in the calculation of the costs. Since such a setup with the purpose of recycling Waelz slag has never been built before, the different parameters regarding the charging are not fully elaborated. As described in the CAPEX part, a total of 7.778 charges is necessary when the converters offer space for 9 t of treatable material. Since the process is continuous, one charge leads into another, so there is no clearly evident line. Keeping in mind that there will be two TBRCs justifies a number of 3.889 charges per vessel every year. By assuming that the time required for a total reduction of the oxides is a little more than one hour – an assumption that is based on the actual experiments performed in the technological part – a 2-shift-model offers enough buffers. Accordingly, various employees could work for a total of 16 hours every day for the whole year, offering a sum of 5840 hours. While enough time is installed to guarantee a smooth running operation, the third and most expensive night shift does not incur. The only disadvantage of this solution represents the fact that the iron bath has to be tapped every time after the second shift and heated as well as molten again in the mornings in order to guarantee a functioning process throughout the day. During the nights, the temperature can be kept at 300-400 °C which means an extra amount of energy. This parameter has, however, already been included by the efficiency factor η_3 in the preceding chapter dealing with energy costs.

9.4.4.1 Labour and Maintenance Costs Realistic Case

As described in the head, a 2-shift-model constitutes the base for the labour cost calculation. Table 65 explains the working time scheme as well as other facts that concern payment of the workers. Each salary amount derives from comparable companies in the metallurgical industry within Central Europe, while neither extra pay nor any bonuses are included in the different amounts.

Table 65: Labour costs for the realistic case

Shifts	2	per day
Hours per Shift	8	h/Shift
Total Hours per Day	16	h/day
Total Hours per Year	5'840	h/year
Salary Manager	63'000	EUR/year
Salary Manager	86'940	USD/year
Salary Shift Leader	42'000	EUR/year
Salary Shift Leader	57'960	USD/year
Salary Blue Colour	28'000	EUR/year
Salary Blue Colour	38'640	USD/year
Number of Managers	-	per shift
Costs Managers	-	USD/year
Number of Shift Leaders	1	per shift
Total Amount SL	2	per year
Costs SL	115'920	USD/year
Number of Blue Colour	1	per Shift and TBRC
Total Amount BC	4	per year
Costs BC	154'560	USD/year
Total Costs Labour	270'480	USD/year

As the construction of the top blown rotary converters only represents an annex to the already existing location, no additional managers will be needed. For every shift there has to be a shift leader who knows the procedures and who is therefore responsible for a smooth operation of both TBRCs. In total, two more employees – one for each vessel – seem to be sufficient since the processes mostly run automated. By adding the different values in Table 65, labour costs of 270.480 USD constitute the result for the realistic case.

Considering the relatively long depreciation time of 20 years for most of the inventory, elevated maintenance expenditures should be assumed. 5 % of the total CAPEX seems to represent an adequate amount as well as a comparable industrial value and sums up to a total of 1.070.636 USD every year.

9.4.4.2 Labour and Maintenance Costs Best Case

The shift model including the different employees remains the same for this scenario. However, the salaries drop by 20 % compared to the realistic case, an aspect that could possibly be achieved by cheaper contracts. Table 66 displays the total labour costs of 216.384 USD/year for this option.

Table 66: Labour costs for the best case

Shifts	2	per day
Hours per Shift	8	h/Shift
Total Hours per Day	16	h/day
Total Hours per Year	5'840	h/year
Salary Manager	50'400	EUR/year
Salary Manager	69'552	USD/year
Salary Shift Leader	33'600	EUR/year
Salary Shift Leader	46'368	USD/year
Salary Blue Colour	22'400	EUR/year
Salary Blue Colour	30'912	USD/year
Number of Managers	-	per shift
Costs Managers	-	USD/year
Number of Shift Leaders	1	per shift
Total Amount SL	2	per year
Costs SL	92'736	USD/year
Number of Blue Colour	1	per Shift and TBRC
Total Amount BC	4	per year
Costs BC	123'648	USD/year
Total Costs Labour	216'384	USD/year

Instead of the 5 % for maintenance, 3 % of the capital expenditure is chosen for the best case scenario. This sum still provides enough reserves for incidental repair work and shows the significantly lower amount of 492.245 USD/year for maintenance purposes.

9.4.4.3 Labour and Maintenance Costs Worst Case

In contrast to the two preceding cases, one additional employee to the shift leader does not guarantee a safe and successful operation mode in the worst case scenario. Two workers per converter will have to be present in order to act when an urgent task has to be done or to do repair and maintenance work. Together with the raised costs that are increased by 20 %, an overall labour amount of 510.048 USD every year constitutes about double the costs when compared with the other options. Table 67 gives information regarding the labour costs for this scenario.

Table 67: Labour costs for the worst case

Shifts	2	per day
Hours per Shift	8	h/Shift
Total Hours per Day	16	h/day
Total Hours per Year	5'840	h/year
Salary Manager	75'600	EUR/year
Salary Manager	104'328	USD/year
Salary Shift Leader	50'400	EUR/year
Salary Shift Leader	69'552	USD/year
Salary Blue Colour	33'600	EUR/year
Salary Blue Colour	46'368	USD/year
Number of Managers	-	per shift
Costs Managers	-	USD/year
Number of Shift Leaders	1	per shift
Total Amount SL	2	per year
Costs SL	139'104	USD/year
Number of Blue Colour	2	per Shift and TBRC
Total Amount BC	8	per year
Costs BC	370'994	USD/year
Total Costs Labour	510'048	USD/year

In this case, the maintenance costs are raised as well and add up to a value of 7 % of the total worst scenario CAPEX. Accordingly, this number is represented by a value of 1.912.713 USD/year.

9.4.5 Transport

Since most of the transportation infrastructure already exists at Befesa, the additional internal transport is the only factor that enlarges the logistic horizon within the plant. Input materials such as Waelz slag or coke breeze on the one hand and end products like zinc oxide or the iron alloy on the other have to be moved permanently for which reason internal transport must not be excluded.

9.4.5.1 Internal Transport Costs Realistic Case

The costs for internal transport lie at around 3 USD/t when looking at comparable companies and industrial concepts. Table 68 shows the amounts of these factors with the interesting aspect that the final products only weigh approximately two thirds of the input materials. This can be explained by the mass of carbon that enters the gaseous state within the process and leaves the system with the exhaust gas. By multiplying the costs per ton with the actual amount of the different materials, a total expense of 465.347 USD/year depicts the result.

Table 68: Internal transport costs for the realistic case

Internal Transport	3	USD/t
Amount Raw Materials	94'510	t/year
Amount Products	60'606	t/year
Total Costs	465'347	USD/year

9.4.5.2 Internal Transport Costs Best Case

Instead of assuming costs of 3 USD/t for the different raw materials and products, the price drops to 2 USD/t. As a reason, the total expenses for the internal transport drop by 33 % to a sum of 310.231 USD/year as can be seen in Table 69.

Table 69: Internal transport costs for the best case

Internal Transport	2	USD/t
Amount Raw Materials	94'510	t/year
Amount Products	60'606	t/year
Total Costs	310'231	USD/year

9.4.5.3 Internal Transport Costs Worst Case

In contrast to the best case, the internal transport costs increase by 33 % to 4 USD/t in the worst case scenario. Table 70 shows that the total costs rise accordingly to 620.462 USD/year by the same percentage.

Table 70: Internal transport costs for the worst case

Internal Transport	4	USD/t
Amount Raw Materials	94'510	t/year
Amount Products	60'606	t/year
Total Costs	620'462	USD/year

9.4.6 Total OPEX

The calculation of the total operational expenditure is performed in the same manner as the one for the CAPEX. The amounts from the raw materials, the refractories, the burner gases and the labour and maintenance costs as well as the internal transport are summed up and a contingency rate is added to the resulting value.

9.4.6.1 Total OPEX Realistic Case

For the realistic case, the total OPEX represents a sum of 14.350.243 USD/year, whereof the broad majority consists of the costs for the raw material coke and the burner gases methane and oxygen. Figure 34 shows the distribution of the different cost drivers, emphasizing the important role of the factors burner gases and raw materials. By including the same contingency rate of 20 % as for the CAPEX, the total operational expenditure results in a value of 17.220.291 USD/year.

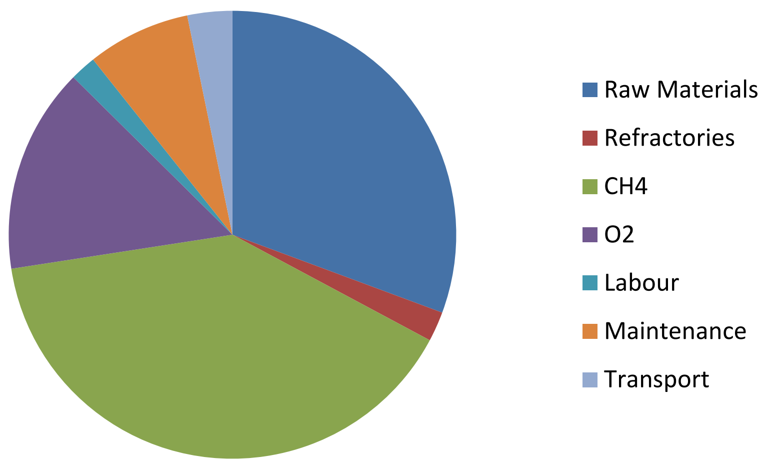

Figure 34: Distribution of the OPEX cost drivers

9.4.6.2 Total OPEX Best Case

For the best case scenario, the same procedure as mentioned is performed, however, the contingency rate possesses the slightly lower value of 15 % compared to the realistic case. Hence, the theoretical amount of 10.282.716 USD/year rises to a total of 11.825.124 USD/year.

9.4.6.3 Total OPEX Worst Case

Unsurprisingly, the total OPEX for the worst case shows the highest value. By adding 25 % – a sum that includes further reserves for unpredictable contingencies – to the 19.303.444 USD/year, the total operational expenditure reaches an amount of 24.129.305 USD/year and proves the significant influence of the coke breeze as well as the burner gases on the overall costs.

9.5 Earnings

This chapter introduces the revenues that are achieved by selling the different products from the recycling process. The main part is presented by the zinc oxide that constitutes the desired compound from the Waelz slag. The price for ZnO can be calculated by multiplying the current rate from the London Metal Exchange (LME) by the factor 0.85 and then subtracting the treatment charge which depends on the quality of the produced oxide. If the zinc oxide complies with the purity requirements for washed ZnO, the treatment charge has a value of 239 USD/t, whereas it rises to 424 USD/t when not reaching these standards and remaining the crude oxide. For the calculation of the actual earnings from the Zn section, the LME price of 2.080 USD/t from the 5th of June 2014 generates the base.[40]

Another important aspect represents the fact of not landfilling the Waelz slag. As the charge for doing so currently is at 20 EUR/t, this amount does not have to be paid but can be added to the earnings instead. Therefore, the process becomes more economical as no fees have to be paid for the input material on the one hand and additional income is achieved without further effort on the other.

9.5.1 Earnings Realistic Case

Table 71 displays the breakdown of all possible revenues. As mentioned in the head, the zinc oxide delivers the biggest part. By using the presented formula, the selling price for ZnO can be calculated for the realistic case. The final product is assumed to meet the standards for the “washed” classification as the most problematic elements such as fluorine, chlorine and the alkali metals either do not enter the process or leave the converter with the off gas which for example is the case for K_2O.

Table 71: Earnings for the realistic case

ZnO		
Current LME Zn	2'080	USD/t
Treatment charge	239	USD/t
Selling Price ZnO	1'529	USD/t
Amount produced	6'972'000	kg/year
Amount produced	6'972	t/year
Total Earnings	10'660'188	USD/year
Iron Alloy		
Selling Price EUR	250	EUR/t
Selling Price USD	345	USD/t
Amount produced	23'800'000	kg/year
Amount produced	23'800	t/year
Total Earnings	8'211'000	USD/year
Slag		
Slag Selling Price	-	USD/t
Amount produced	29'823'500	kg/year
Amount produced	29'823.5	t/year
Total Earnings	-	USD/year
Exhaust Gas		
Gas Selling Price	-	USD/t
Amount produced	32'382'553	kg/year
Amount produced	32'382.6	t/year
Total Earnings	-	USD/year
Pig Iron Bath		
Bath Selling Price	-	USD/t
Amount produced	10'000	kg/year
Amount produced	10	t/year
Total Earnings	-	USD/year
Other Earnings		
Waelz Slag Use EUR	20.0	EUR/t
Waelz Slag Use USD	27.6	USD/t
Amount of Waelz Slag	70'000'000	kg/year
Amount of Waelz Slag	70'000	t/year
Total Earnings	1'932'000	USD/year
Sum Earnings	20'803'188	USD/year

The amount of the 6.972 annually produced tons of oxide derives from the mass balance which implies a complete reduction in the recycling process. When combined with the current price, total earnings of 10.660.188 USD/t represent the result.

Since the Waelz slag still contains a considerable amount of Fe which reaches about 33 % of the total weight, an iron alloy constitutes the second income source. Usual selling prices for alloys of this type range between 200-300 EUR/t for which reason the arithmetic mean serves as reference value for the realistic case. By combining the 23.800 annual tonnes from the mass balance with this number, an additional profit of 8.211.000 USD/year originates.

The obtained slag from the process shows an ambivalent nature. At some point it may be sold to the construction industry for purposes such as road construction, however, if there is no need it might as well be sent to landfill which is accompanied with a depositing fee. Therefore, a zero-sum assumption constitutes the best solution for the slag. Another component that does not influence the earnings is presented by the off gas. The mixture rich in carbon monoxide and carbon dioxide leaves the process without any further treatment after passing the exhaust system. The 10 t for the iron bath are not sold after one year as this component only represents the first charging of the converters and also includes possible losses. By adding the sums of the ZnO earnings, the iron alloy and the revenues from not landfilling the Waelz slag, a total profit of 20.803.188 USD/year seems to constitute a satisfying result. An important step proves to be the control of the mass balance that shows a total amount of 94.510 annual tonnes when also considering the elements present in smaller concentrations within the different products. Figure 36 graphically demonstrates the distribution of the three different income sources and emphasizes the importance of the ZnO section.

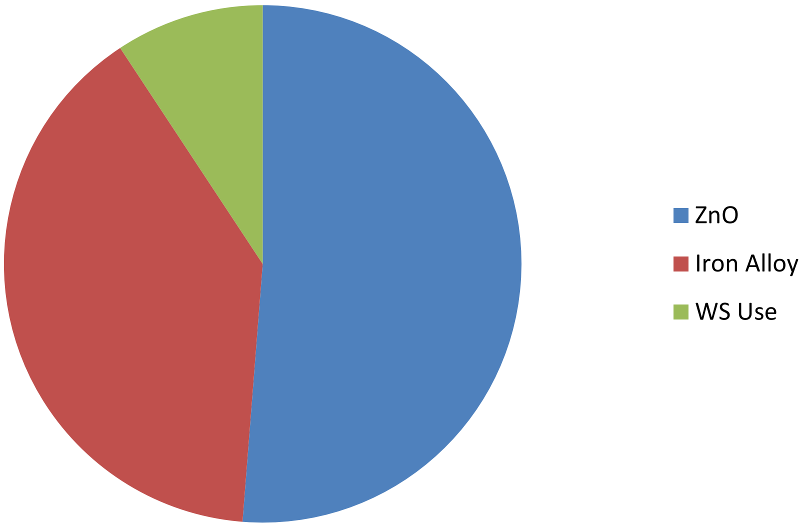

Figure 35: Distribution of the different income sources

9.5.2 Earnings Best Case

The most important aspect that the best case has in common with the preceding one is the fact that the sold zinc oxide is also expected to comply with the “washed” standard. By assuming an LME zinc price that is increased by 10 % and considering the values from the mass balance, total earnings of 11.892.838 USD/year originate for this compound – a detail which is can also be seen in Table 72.

Table 72: Earnings for the best case

ZnO		
Current LME Zn	2'288	USD/t
Treatment charge	239	USD/t
Selling Price ZnO	1'706	USD/t
Amount produced	6'972'000	kg/year
Amount produced	6'972	t/year
Total Earnings	11'892'838	USD/year
Iron Alloy		
Selling Price EUR	300	EUR/t
Selling Price USD	414	USD/t
Amount produced	23'800'000	kg/year
Amount produced	23'800	t/year
Total Earnings	9'853'200	USD/year
Slag		
Slag Selling Price	-	USD/t
Amount produced	29'823'500	kg/year
Amount produced	29'823.5	t/year
Total Earnings	-	USD/year
Exhaust Gas		
Gas Selling Price	-	USD/t
Amount produced	32'382'553	kg/year
Amount produced	32'382.6	t/year
Total Earnings	-	USD/year
Pig Iron Bath		
Bath Selling Price	-	USD/t
Amount produced	10'000	kg/year
Amount produced	10	t/year
Total Earnings	-	USD/year
Other Earnings		
Waelz Slag Use EUR	25.0	EUR/t
Waelz Slag Use USD	34.5	USD/t
Amount of Waelz Slag	70'000'000	kg/year
Amount of Waelz Slag	70'000	t/year
Total Earnings	2'415'000	USD/year
Sum Earnings	24'161'038	USD/year

For the best case scenario, the selling price for the iron alloy reaches the maximum of 300 EUR/t or 414 USD/t which is why the earnings for this compound also increase to a sum of 9.853.200 USD/year. Alloying elements and impurities have to be considered for this aspect and will later be described in detail. The same rules as in the preceding case apply for the slag, the exhaust gas and the pig iron bath for which reason they do not have an influence on the income. Regarding the use of the Waelz slag, an amount of 25 EUR/t is paid which means an increase of 5 EUR/t. This value originates from laws regarding landfilling activities in selective Central European countries. The overall earnings for this scenario sum up to 24.161.038 USD/year and excel the realistic case by more than 3 million USD/year.

9.5.3 Earnings Worst Case

Identical to the other cases, the amount of produced ZnO remains the same, whereas the LME Zn price drops by 10 % in this scenario. The main difference compared to the realistic case is the fact that the oxide does not meet the standards in order to be sold as “washed” quality. As a reason, the treatment charge increases to a number of 424 USD/t which represents the value for the crude zinc oxide. Hence, Table 73 demonstrates that the earnings from the zinc section add up to 8.137.718 USD/t.

Table 73: Earnings for the worst case

ZnO		
Current LME Zn	1'872	USD/t
Treatment charge	424	USD/t
Selling Price ZnO	1'167	USD/t
Amount produced	6'972'000	kg/year
Amount produced	6'972	t/year
Total Earnings	8'137'718	USD/year
Iron Alloy		
Selling Price EUR	200	EUR/t
Selling Price USD	276	USD/t
Amount produced	23'800'000	kg/year
Amount produced	23'800	t/year
Total Earnings	6'568'800	USD/year
Slag		
Slag Selling Price	-	USD/t
Amount produced	29'823'500	kg/year
Amount produced	29'283.5	t/year
Total Earnings	-	USD/year
Exhaust Gas		
Gas Selling Price	-	USD/t
Amount produced	32'382'553	kg/year
Amount produced	32'382.6	t/year
Total Earnings	-	USD/year
Pig Iron Bath		
Bath Selling Price	-	USD/t
Amount produced	10'000	kg/year
Amount produced	10	t/year
Total Earnings	-	USD/year
Other Earnings		
Waelz Slag Use EUR	15.0	EUR/t
Waelz Slag Use USD	20.7	USD/t
Amount of Waelz Slag	70'000'000	kg/year
Amount of Waelz Slag	70'000	t/year
Total Earnings	1'449'000	USD/year
Sum Earnings	16'155'518	USD/year

In the worst case scenario, the selling price for the iron alloy constitutes the lowest average value when regarding the metallurgical industry. This means various impurities within the material for which reason its field of application is limited. The overall earnings for the iron alloy sum up to an amount of 6.568.800 USD/t. As described in the realistic case, the originating slag, the exhaust gas and the pig iron bath do not have any influence on the profit. Lowering the landfilling fee for the Waelz oxide to 15 EUR/t also means reduced earnings for its use. Therefore, the benefit from recycling 70.000 USD/t of slag leads to a value of 1.449.000 USD/year which displays total earnings of 16.155.518 USD/year for the worst case scenario.

9.6 Total Expenditure

The combination of the capital expenditure, the operational expenditure and the earnings delivers information regarding the total costs. At the end, these decide if the project is going to be executed or not. Since the objective of every economic action is represented by the value enhancement of the corporation, the final result has to be positive. All assumptions that were made in the previous calculations have a significant influence on the total expenditure for which reason the most important ones are presented in this chapter.

In dependence on up-to-date prices and process parameters, the factors that sum up to the realistic case represent the most probable outcome for the project. The CAPEX, OPEX and earnings are considered for the life span of 20 years and discounted to the current date in order to present the project’s value at today’s conditions. To perform this task, the discounted cash flow method is used as it shows a realistic and clear setup. The discount factor is represented by the weighted average cost of capital or WACC which is a financial number that is equal to a company’s general cost of capital. It includes factors such as the amount of equity as well as the debts and the interest rates for both of them. Nowadays, the WACC for companies working in the metallurgical industry in Central Europe reaches a value of approximately 10 %. For this reason, the discount rate used for the calculations is at 10 %, however, it can easily be modified by Befesa, so slightly incorrect assumptions can be corrected without any arising problems. The discounted cash flow method does not use depreciation as a factor. Consequently, the capital expenditure is considered at the beginning of the project and when reaching the end of life time, final values are added to the capital after having been discounted as well. The calculation of the different parameters is performed without the consideration of taxes as these vary in every country and influence the result only quantitatively.

The first step of the presented method consists of declaring the different factors that are represented by the earnings, OPEX and CAPEX. For the profit as well as for the operational expenditure inflation plays an important role. The European Central Bank aims at an inflation rate of 2 % over the medium term for which reason this value represents the reference.[41] The percentage is calculated for the project's life time of 20 years and is then discounted to the current date too. This number as well as the discount rate are always included at the end of every year and accordingly characterize the worst yet realistic case because profits are only discounted at the very last point. In the next step, the three different components are summed up for each year and represent the annual cash flow. Independent from the regarded case, this value always shows a negative number because of the investment costs that incur when the project starts. This annual cash flow is then multiplied by the discount factor, a number that includes the actual discount rate – which is equivalent to the weighted average cost of capital – and the amount of years. As a result, the accumulated cash flow at present value is determined. It represents the total flow of liquid resources for each of the 20 years. Figure 36 demonstrates the impact of the discount rate for the realistic case scenario. The higher its value, the faster the accumulated cash flow at present value decreases. By considering the weighted average cost of capital of 10 %, a drop from 3.582.897 USD after the first year to a total amount of 853.447 USD at the end of the project can be observed.

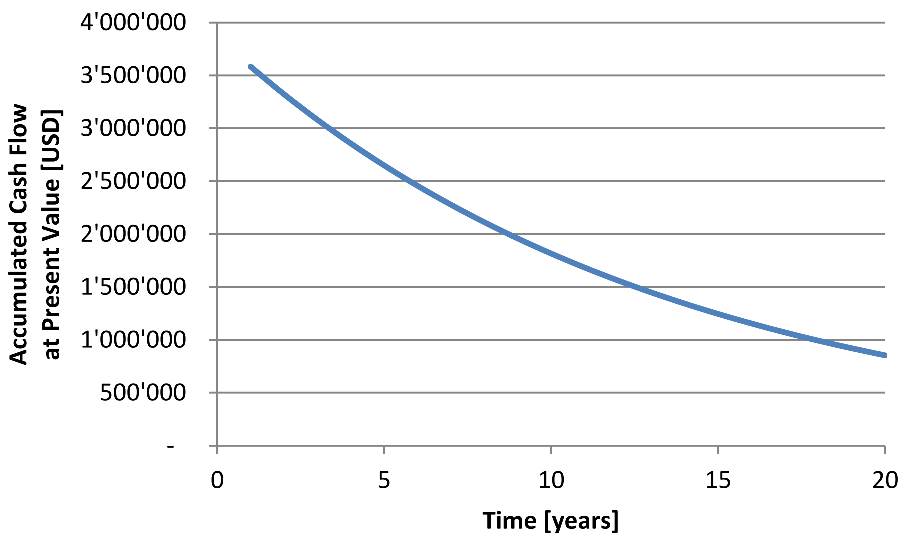

Figure 36: Impact of the discount factor

Adding the different cash flows constitutes the last step of the calculation and leads to the net present value. This number expresses the project's total value at the end of every year and is the most important factor for an investment decision.

9.6.1 Total Expenditure Realistic Case

For the realistic case scenario, the CAPEX, OPEX and earnings from the relevant chapters apply and can be seen in Table 74 for the first 10 years of the project. After including the inflation for the profit and the operational expenditure, the free cash flow is calculated. The step of also including the capital expenditure which incurs at the beginning of the investment results in the annual cash flow. These numbers are multiplied by the discount factor that is annually influenced by the WACC of 10 %. As a result, the NPV of the first half of the project's life time is obtained by adding the accumulated cash flow at present value.

Table 74: Economic values showing the first half of the realistic case

Time	1	2	3	4	5	years
Earnings	20'803'188	20'803'188	20'803'188	20'803'188	20'803'188	USD
Inflation	2 %	2 %	2 %	2 %	2 %	
I. Factor	100.0 %	102.0 %	104.0 %	106.1 %	108.2 %	
Earnings a. I.	20'803'188	21'219'252	21'643'637	22'076'510	22'518'040	USD
OPEX	-17'220'291	-17'220'291	-17'220'291	-17'220'291	-17'220'291	USD
OPEX a. I:	-17'220'291	-17'564'697	-17'915'991	-18'274'311	-18'639'797	USD
Free CF	3'582'897	3'654'555	3'727'646	3'802'199	3'878'243	USD
CAPEX	-21'412'728	0	0	0	0	USD
Annual CF	-17'829'831	3'654'555	3'727'646	3'802'199	3'878'243	USD
D.R./WACC	10 %	10 %	10 %	10 %	10 %	
D. Factor	100.0 %	110.0 %	121.0 %	133.1 %	146.4 %	
ACF at PV	-17'829'831	3'322'322	3'080'699	2'856'648	2'648'892	USD
NPV	-17'829'831	-14'507'509	-11'426'810	-8'570'162	-5'921'270	USD
Time	6	7	8	9	10	years
Earnings	20'803'188	20'803'188	20'803'188	20'803'188	20'803'188	USD
Inflation	2 %	2 %	2 %	2 %	2 %	
I. Factor	110.4 %	112.6 %	114.9 %	117.2 %	119.5 %	
Earnings a.I.	22'968'401	23'427'769	23'896'324	24'374'250	24'861'735	USD
OPEX	-17'220'291	-17'220'291	-17'220'291	-17'220'291	-17'220'291	USD
OPEX a.I.	-19'012'593	-19'392'845	-19'780'702	-20'176'316	-20'579'842	USD
Free CF	3'955'807	4'034'924	4'115'622	4'197'935	4'281'893	USD
CAPEX	0	0	0	0	0	USD
Annual CF	3'955'807	4'034'924	4'115'622	4'197'935	4'281'893	USD
DR/WACC	10 %	10 %	10 %	10 %	10 %	
D. Factor	161.1 %	177.2 %	194.9 %	214.4 %	235.8 %	
ACF at PV	2'456'245	2'277'609	2'111'965	1'958'367	1'815'941	USD
NPV	-3'465'025	-1'187'416	924'549	2'882'917	4'698'858	USD

As can be seen in Table 74, the realistic case scenario delivers a positive result for the NPV after a time of 8 years from today's point of view. All further cash flows increase the net present value even more. Consequently, the NPV reaches a final value of 17.140.253 USD at the project's end of life. At this point, the CAPEX shows a positive number as well due to the final value of different facilities such as land or the building. Table 75 provides the important economic values of the second half of the project and highlights the final net present value for the realistic case scenario.

Table 75: Economic values showing the second half of the realistic case

Time	11	12	13	14	15	years
Earnings	20'803'188	20'803'188	20'803'188	20'803'188	20'803'188	USD
Inflation	2 %	2 %	2 %	2 %	2 %	
I. Factor	121.9 %	124.3 %	126.8 %	129.4 %	131.9 %	
Earnings a.I.	25'358'970	25'866'149	26'383'472	26'911'142	27'449'365	USD
OPEX	-17'220'291	-17'220'291	-17'220'291	-17'220'291	-17'220'291	USD
OPEX a.I.	-20'991'439	-21'411'268	-21'839'493	-22'276'283	-22'721'809	USD
Free CF	4'367'531	4'454'882	4'543'979	4'634'859	4'727'556	USD
CAPEX	0	0	0	0	0	USD
Annual CF	4'367'531	4'454'882	4'543'979	4'634'859	4'727'556	USD
D.R./WACC	10 %	10 %	10 %	10 %	10 %	
D. Factor	259.4 %	285.3 %	313.8 %	345.2 %	379.7 %	
ACF at PV	1'683'872	1'561'409	1'447'852	1'342'554	1'244'913	USD
NPV	6'382'730	7'944'139	9'391'991	10'734'544	11'979'457	USD
Time	16	17	18	19	20	years
Earnings	20'803'188	20'803'188	20'803'188	20'803'188	20'803'188	USD
Inflation	2 %	2 %	2 %	2 %	2 %	
I. Factor	134.6 %	137.3 %	140.0 %	142.8 %	145.7 %	
Earnings a.I.	27'998'352	28'558'319	29'129'485	29'712'075	30'306'317	USD
OPEX	-17'220'291	-17'220'291	-17'220'291	-17'220'291	-17'220'291	USD
OPEX a.I..	-23'176'245	-23'639'770	-24'112'565	-24'594'816	-25'086'713	USD
Free CF	4'822'107	4'918'549	5'016'920	5'117'259	5'219'604	USD
CAPEX	0	0	0	0	1'037'256	USD
Annual CF	4'822'107	4'918'549	5'016'920	5'117'259	6'256'861	USD
D.R./WACC	10 %	10 %	10 %	10 %	10 %	
D. Factor	417.7 %	459.5 %	505.4 %	556.0 %	611.6 %	
ACF at PV	1'154'374	1'070'420	992'571	920'384	1'023'047	USD
NPV	13'133'832	14'204'251	5'196'822	16'117'206	17'140'253	USD

9.6.2 Total Expenditure Best Case

In contrast to the realistic case, this scenario includes the best possible presented assumptions for costs as well as earnings, however, the calculation scheme is identical with the one in the preceding chapter. Table 76 shows the financial numbers for the first 10 years of the project's life time.

Table 76: Economic values showing the first half of the best case

Time	1	2	3	4	5	years
Earnings	24'161'038	24'161'038	24'161'038	24'161'038	24'161'038	USD
Inflation	2 %	2 %	2 %	2 %	2 %	
I. Factor	100.0 %	102.0 %	104.0 %	106.1 %	108.2 %	
Earnings a.I.	24'161'038	24'644'258	25'137'144	25'639'886	26'152'684	USD
OPEX	-17'220'291	-17'220'291	-17'220'291	-17'220'291	-17'220'291	USD
OPEX a.I.	-17'220'291	-17'564'697	-17'915'991	-18'274'311	-18'639'797	USD
Free CF	6'940'746	7'079'561	7'221'152	7'365'576	7'512'887	USD
CAPEX	-21'412'728	0	0	0	0	USD
Annual CF	-14'471'982	7'079'561	7'221'152	7'365'576	7'512'887	USD
D.R./WACC	10 %	10 %	10 %	10 %	10 %	
D. Factor	100.0 %	110.0 %	121.0 %	133.1 %	146.4 %	
ACF at PV	-14'471'982	6'435'965	5'967'895	5'533'866	5'131'403	USD
NPV	-14'471'982	-8'036'017	-2'068'122	3'465'744	8'597'146	USD
Time	6	7	8	9	10	years
Earnings	24'161'038	24'161'038	24'161'038	24'161'038	24'161'038	USD
Inflation	2 %	2 %	2 %	2 %	2 %	
I. Factor	110.4 %	112.6 %	114.9 %	117.2 %	119.5 %	
Earnings a.I.	26'675'738	27'209'253	27'753'438	28'308'506	28'874'676	USD
OPEX	-17'220'291	-17'220'291	-17'220'291	-17'220'291	-17'220'291	USD
OPEX a.I.	-19'012'593	-19'392'845	-19'780'702	-20'176'316	-20'579'842	USD
Free CF	7'663'145	7'816'408	7'972'736	8'132'191	8'294'834	USD
CAPEX	0	0	0	0	0	USD
Annual CF	7'663'145	7'816'408	7'972'736	8'132'191	8'294'834	USD
D.R./WACC	10 %	10 %	10 %	10 %	10 %	
D. Factor	161.1 %	177.2 %	194.9 %	214.4 %	235.8 %	
ACF at PV	4'758'210	4'412'158	4'091'274	3'793'727	3'517'819	USD
NPV	13'355'356	17'767'515	21'858'789	25'652'516	29'170'335	USD

For this case, the NPV already takes a positive value after only 4 years, hence making this scenario more profitable than the preceding one. The accumulated cash flows are constantly higher and lead to a net present value of 53.063.281 USD at the end, as seen in Table 77. This number is more than three times higher than the result for the realistic case and shows the big possible advantage of investing in the new recycling concept of Waelz slag when considering the best case.

Table 77: Economic values showing the second half of the best case

Time	11	12	13	14	15	years
Earnings	24'161'038	24'161'038	24'161'038	24'161'038	24'161'038	USD
Inflation	2 %	2 %	2 %	2 %	2 %	
I. Factor	121.9 %	124.3 %	126.8 %	129.4 %	131.9 %	
Earnings a.I.	29'452'170	30'041'213	30'642'038	31'254'878	31'879'976	USD
OPEX	-17'220'291	-17'220'291	-17'220'291	-17'220'291	-17'220'291	USD
OPEX a.I.	-20'991'439	-21'411'268	-21'839'493	-22'276'283	-22'721'809	USD
Free CF	8'460'731	8'629'946	8'802'545	8'978'595	9'158'167	USD
CAPEX	0	0	0	0	0	USD
Annual CF	8'460'731	8'629'946	8'802'545	8'978'595	9'158'167	USD
D.R./WACC	10 %	10 %	10 %	0 %	10 %	
D. Factor	259.4 %	285.3 %	313.8 %	345.2 %	379.7 %	
ACF at PV	3'261'978	3'024'743	2'804'762	2'600'779	2'411'632	USD
NPV	32'432'313	35'457'057	38'261'819	40'862'598	43'274'230	USD

Time	16	17	18	19	20	years
Earnings	24'161'038	24'161'038	24'161'038	24'161'038	24'161'038	USD
Inflation	2 %	2 %	2 %	2 %	2 %	
I. Factor	134.6 %	137.3 %	140.0 %	142.8 %	145.7 %	
Earnings a.I.	32'517'576	33'167'927	33'831'286	34'507'911	35'198'070	USD
OPEX	-17'220'291	-17'220'291	-17'220'291	-17'220'291	-17'220'291	USD
OPEX a.I.	-23'176'245	-23'639'770	-24'112'565	-24'594'816	-25'086'713	USD
Free CF	9'341'331	9'528'157	9'718'720	9'913'095	10'111'357	USD
CAPEX	0	0	0	0	734'914	USD
Annual CF	9'341'331	9'528'157	9'718'720	9'913'095	10'846'271	USD
D.R./WACC	10 %	10 %	10 %	10 %	10 %	
D. Factor	417.7 %	459.5 %	505.4 %	556.0 %	611.6 %	
ACF at PV	2'236'240	2'073'605	1'922'797	1'782'957	1'773'452	USD
NPV	45'510'470	47'584'075	49'506'872	51'289'829	53'063'281	USD

9.6.3 Total Expenditure Worst Case

The evaluation of the economic values is performed analogical to the two preceding ones. Table 78 demonstrates the first half of the negative scenario and includes the capital expenditure, the operational expenditure as well as the earnings from the worst case calculations performed earlier.

Table 78: Economic values showing the first half of the worst case

Time	1	2	3	4	5	years
Earnings	16'155'518	16'155'518	16'155'518	16'155'518	16'155'518	USD
Inflation	2 %	2 %	2 %	2 %	2 %	
I. Factor	100.0 %	102.0 %	104.0 %	106.1 %	108.2 %	
Earnings a.I.	16'155'518	16'478'629	16'808'201	17'144'365	17'487'253	USD
OPEX	-24'129'305	-24'129'305	-24'129'305	-24'129'305	-24'129'305	USD
OPEX a.I.	-24'129'305	-24'611'891	-25'104'129	-25'606'212	-26'118'336	USD
Free CF	-7'973'787	-8'133'263	-8'295'928	-8'461'846	-8'631'083	USD
CAPEX	-27'324'465	0	0	0	0	USD
Annual CF	-35'298'252	-8'133'263	-8'295'928	-8'461'846	-8'631'083	USD
D.R./WACC	10 %	10 %	10 %	10 %	10 %	
D. Factor	100.0 %	110.0 %	121.0 %	133.1 %	146.4 %	
ACF at PV	-35'298'252	-7'393'875	-6'856'139	-6'357'510	-5'895'146	USD
NPV	-35'298'252	-42'692'127	-49'548'266	-55'905'776	-61'800'922	USD
Time	6	7	8	9	10	years
Earnings	16'155'518	16'155'518	16'155'518	16'155'518	16'155'518	USD
Inflation	2 %	2 %	2 %	2 %	2 %	
I. Factor	110.4 %	112.6 %	114.9 %	117.2 %	119.5 %	
Earnings a.I.	17'836'998	18'193'738	18'557'612	18'928'765	19'307'340	USD
OPEX	-24'129'305	-24'129'305	-24'129'305	-24'129'305	-24'129'305	USD
OPEX a.I.	-26'640'703	-27'173'517	-27'716'987	-28'271'327	-28'836'753	USD
Free CF	-8'803'705	-8'979'779	-9'159'375	-9'342'562	-9'529'413	USD
CAPEX	0	0	0	0	0	USD
Annual CF	-8'803'705	-8'979'779	-9'159'375	-9'342'562	-9'529'413	USD
D.R./WACC	10 %	10 %	10 %	10 %	10 %	
D. Factor	161.1 %	177.2 %	194.9 %	214.4 %	235.8 %	
ACF at PV	-5'466'408	-5'068'851	-4'700'207	-4'358'374	-4'041'402	USD
NPV	-67'267'330	-72'336'181	-77'036'389	-81'394'763	-85'436'165	USD

Due to the fact that the OPEX is constantly and significantly higher than the earnings, the net present value never reaches a positive number in this scenario. Table 79 demonstrates the financial numbers for the second half and shows that the final NPV is at -112.539.162 USD for a time span of 20 years which displays a strongly negative result and does therefore not promote the idea of investing in a new recycling concept of accumulating Waelz slag.

Table 79: Economic values showing the second half of the worst case

Time	11	12	13	14	15	years
Earnings	16'155'518	16'155'518	16'155'518	16'155'518	16'155'518	USD
Inflation	2 %	2 %	2 %	2 %	2 %	
I. Factor	121.9 %	124.3 %	126.8 %	129.4 %	131.9 %	
Earnings a.I.	19'693'487	20'087'357	20'489'104	20'898'886	21'316'863	USD
OPEX	-24'129'305	-24'129'305	-24'129'305	-24'129'305	-24'129'305	USD
OPEX a.I.	-29'413'488	-30'001'758	-30'601'793	-31'213'829	-31'838'106	USD
Free CF	-9'720'002	-9'914'402	-10'112'690	-10'314'944	-10'521'242	USD
CAPEX	0	0	0	0	0	USD
Annual CF	-9'720'002	-9'914'402	-10'112'690	-10'314'944	-10'521'242	USD
D.R./WACC	10 %	10 %	10 %	10 %	10 %	
D. Factor	259.4 %	85.3 %	313.8 %	345.2 %	379.7 %	
ACF at PV	-3'747'481	-3'474'937	-3'222'215	-2'987'872	-2'770'572	USD
NPV	-89'183'646	-92'658'583	-95'880'798	-98'868'670	-101'639'242	USD
Time	16	17	18	19	20	years
Earnings	16'155'518	16'155'518	16'155'518	16'155'518	16'155'518	USD
Inflation	2 %	2 %	2 %	2 %	2 %	
I. Factor	134.6 %	137.3 %	140.0 %	142.8 %	145.7 %	
Earnings a.I.	21'743'201	22'178'065	22'621'626	23'074'059	23'535'540	USD
OPEX	-24'129'305	-24'129'305	-24'129'305	-24'129'305	-24'129'305	USD
OPEX a.I.	-32'474'868	-33'124'365	-33'786'853	-34'462'590	-35'151'841	USD
Free CF	-10'731'667	-10'946'301	-11'165'227	-11'388'531	-11'616'302	USD
CAPEX	0	0	0	0	1'272'451	USD
Annual CF	-10'731'667	-10'946'301	-11'165'227	-11'388'531	-10'343'850	USD
D.R./WACC	0 %	10 %	10 %	10 %	10 %	
D. Factor	417.7 %	459.5 %	505.4 %	556.0 %	611.6 %	
ACF at PV	-2'569'076	-2'382'234	-2'208'981	-2'048'327	-1'691'302	USD
NPV	-104'208'317	-106'590'551	-108'799'532	-110'847'859	-112'539'162	USD

10 Discussion of the Results

Since the realistic case includes all the current and necessary information for the realization of the new Waelz slag recycling concept, it constitutes the core for discussion. Based on the described facts and assumptions, a net present value of 17.140.253 USD represents the achievable result within 20 years. In general, the amount of the input material coke and the temperature at which the raw materials are charged into the converters display the main influence factors. As already mentioned in the economic part, the stoichiometric ratio of C only requires approximately one third of the actual amount used in the calculations. This overdosage can be explained by the trials performed on laboratory scale where no satisfying reduction of the oxides could be achieved unless carbon was present in extent. As a matter of fact, it is easy to imagine that this effect does not play such an important role when performing the recycling process in TBRCs of actual size. By further investigating the conditions inside the converters, an enhancement of the carbon performance is definitely possible. The act of altering the CH_4:O_2 ratio when charging coke breeze into the vessel and hence guaranteeing reducing instead of oxidizing conditions displays a step in the right direction. If the Waelz slag to carbon ratio is lowered to 10:3 instead of 10:3.5, the operational expenditure would decrease by approximately 1.1 million USD every year. Therefore, the total costs are reduced significantly and a positive NPV could already be achieved after 6 instead of 8 years. By lowering the actual amount to a ratio of approximately twice the stoichiometric coke needed, 2 million USD can be saved annually and therefore guarantee a profitable operation even quicker. In addition, the burn-off of the excess carbon leads to a lower amount of CH_4 that is required to heat up the input materials. This slight change in the amount of used C shows imposingly what potential lies in the modification and enhancement of this input parameter. Accordingly, the financial values presented in the economic part must always be regarded critically, bearing in mind the dependency from the main influence factors.

As already mentioned, the temperature at which the Waelz slag is charged into the top blown rotary converter constitutes the other very important aspect in the cost calculation. In the realistic case, ϑ takes a value of 400 °C which means that the charging is performed only a short time after leaving the Waelz kiln. Consequently, adequate containers will have to guarantee the efficient and unproblematic transportation of this material. By assuming an even quicker loading and hence utilizing the highest possible charging temperature of 600 °C, a decrease of approximately 900.000 Nm³ of CH_4 can be achieved. Since almost the same amount of oxygen is saved simultaneously, the operational expenditure drops by 1.267.718 USD/year. Modifying the transportation of the Waelz slag does not seem to constitute a serious problem for which reason this amount could easily be cut down. On the contrary, if the direct use of the Waelz slag is not possible and it has to be heated inside the TBRC from an average temperature of 25 °C, additional costs of 2.178.848 USD/year arise. This amount impressively emphasizes the importance of utilizing the process heat from the former recycling step in the Waelz kiln.

Beside the coke ratio and the input temperature of the Waelz slag, there are some other important factors that influence the result of the calculation. The weighted average cost of capital of 10 % which equals the discount factor only represents an estimated average value of comparable investments. By slightly lowering the number to 8 %, the NPV for the investment time of 20 years increases by 5.618.936 USD and would therefore make the project more profitable. In contrast, a rise of 2 % to a percentage of 12 % would deteriorate the result by 4.485.626 USD. These numbers show that the knowledge of the exact WACC is essential for a correct calculation of the overall profitability.

The dependency of the zinc price from the stock market also displays an uncertainty factor. In the year 2009, the selling value exceeded the 2.600 USD/t mark which displays a considerably higher amount than today's 2.080 USD/t.[40] Experts forecast an increase in the selling price for the future which would show a positive influence on the project's earnings as ZnO constitutes the main product from the recycling process of Waelz slag. The price for the produced iron alloy strongly depends on the demand from the steel industry. Quality aspects and their influences on the selling values as well as the consequences play an important role and will be highlighted in the following chapter. The chosen depreciation time of the inventory also constitutes a significant factor in the calculation. The long periods for items such as the converters, the hoppers and the exhaust system can be explained by the elevated costs for maintenance. As a result, all machines keep their operational reliability until the end of the project. Since the process runs on a two shift model, there is enough time to perform modification and repair work.

Beside the realistic situation, the best and the worst case scenario deliver important and informative aspects too. For the first one, the costs for raw materials and other factors are reduced by 20 % in most of the cases, whereas they increase by the same amount for the other. This leads to the higher NPV of 53.063.281 USD when considering the optimistic values and the negative number of -112.539.162 USD when taking the pessimistic ones for a time span of 20 years. This information is also highlighted and compared graphically in Figure 37.

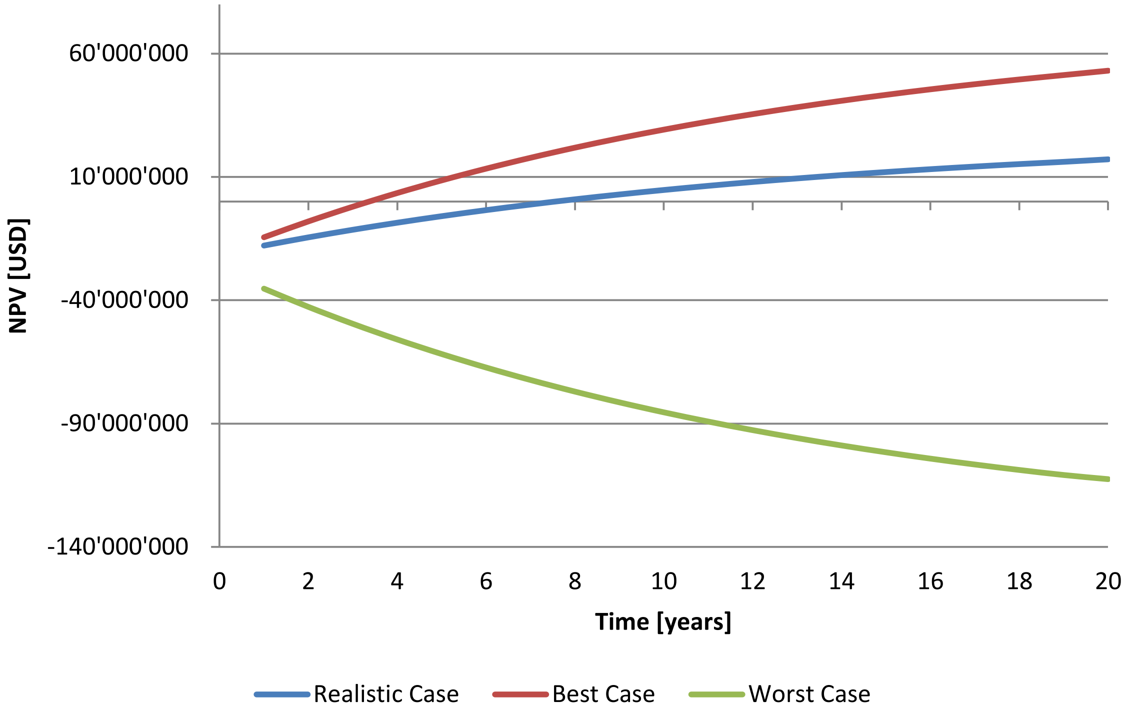

Figure 37: NPV comparison between the three scenarios

The net present value that is represented by the green line in Figure 37 demonstrates the worst case possible where all of the undesirable assumptions occur – a scenario which will not happen when accurately calculating the different input parameters. The more precisely the research work is done, the closer the result should approach the realistic or even the best case.

An interesting aspect that leaves space for interpretation is presented by the contingency costs for the capital as well as the operational expenditure. The relatively high value of 20 % for the realistic case can be justified by the fact that this type of project has never been performed before. Hence, this percentage leaves sufficient reserves for unexpected events and the opportunity of non-effective costs and therefore additional profit if the value shows to be below this 20 %. Even when regarding the best case scenario, the contingency costs of 15 % represent a high number that should prevent the project from unpredictable events.

Since most of the values are based on assumptions, the results do not represent reality, however, they show the broad horizon of the new recycling concept. Moreover, by investigating the industrial parameters even further and performing economic analyses, the concept can be adapted and the new values easily be recalculated. In addition, the question concerning a financing plan will have to be answered as well in order to make a decision.

The trials performed in the laboratory constitute an excellent basis for the operation parameters of the actual size top blown rotary converters. Successful experiments have shown that a reduction of the desired compounds – which mainly consist of ZnO and iron oxides – is achievable. By performing additional trials on industrial scale and varying different parameters, better process conditions will be achieved and the yield can be increased. Due to the spark spectroscopy tests as well as the wet-chemical analyses in the laboratory, the distribution of the different elements that are present in the process can be observed. Manganese for instance shows to move to the slag which is the result of the reducing conditions inside the converter. In comparison to the submerged arc furnace, the TBRC does not guarantee the same reduction degree, however, the elements zinc and iron do get reduced. Therefore, the top blown rotary converter proves to be the right reaction vessel. Additionally, a considerable advantage of the TBRC compared to the submerged arc furnace is its highly flexible operation mode.

To sum up, technological trials as well as economic calculations based on reference values from comparable projects show that the new concept of recycling Waelz slag in a top blown rotary converter is achievable in both aspects. As a matter of course, further experiments will have to be performed in order to find the best possible operation conditions and consequently reduce the amount of charged coke. On the other hand, the financial values will have to be revised and modified, so the calculation is as close to reality as possible.

11 Product Quality Influence on the Profitability

This chapter presents the various aspects of the product quality on the economics of the new recycling concept for Waelz slag. When observing the project's probable earnings, two main factors appear. On the one hand the regained zinc oxide represents the main selling product, whereas on the other the produced iron alloy also provides a significant percentage of the profit.

When looking at the Zn section, especially impurities such as chlorine and fluorine have a substantial influence on the product quality. Other components like alkali metal compounds can also show a negative behaviour in several application areas. Whereas the so called crude zinc oxide that usually derives from the Waelz process has to undergo a further treatment step like a cleaning process in order to meet the high quality standards which are required by many industrial sectors, the washed oxide can be sold directly. In addition to this aspect, the produced quality also influences the treatment charge that must be paid by the producing company. While this fee is represented by a value of 239 USD/t for the higher quality product when considering the value in June 2014, a total of 424 USD/t and therefore almost double the price has to be paid for the crude version. This means additional costs of 185 USD/t and consequently a lower profit when not meeting the quality standards.

This aspect shows a big influence on the overall profitability of the Waelz slag recycling method. As a reason of similar results from the experiments performed at the University of Leoben and the fact that most of the undesired elements already leave the process in the Waelz kiln, the realistic scenario assumes the production of washed zinc oxide. The final product shows low impurity grades regarding chlorine, fluorine as well as alkali metals. Hence, no additional cleaning step is necessary and the product can be sold directly without any further treatment. If the ZnO does not meet these standards and therefore must be classified as crude oxide, additional costs of 1.289.838 USD would accumulate annually when considering a Waelz slag input of 70.000 t/year. This would significantly lower the profit and consequently the net present value of the whole project. As a matter of fact, these numbers show the essential influence of the product quality on the economic considerations. A possible antidote against increased impurity levels within the product is represented by the two-stage process that has been described earlier in Figure 13. Here, the dust that comes from the electric steel industry experiences a pre-treatment where the most volatile components such as chlorine, fluorine and alkali metal compounds are selectively volatilized and leave the process. What stays behind, is the so called Clinker that can be fed directly into the Waelz kiln. Since the majority of the undesirable elements is terminated during this procedure, they do not accumulate in the next step, the actual recycling process of the produced slag.

Beside the zinc oxide, the iron alloy that accumulates within the continuous recycling process represents the second and possibly even more important component when considering quality aspects. As commonly known, Fe globally displays the quantitatively most produced metal, hence offering an endless list of different alloys and purity grades. Accordingly, the price ranges per ton also vary tremendously from low values to numbers in the high thousands per ton for special steels.

When looking at Table 26 which states the chemical composition of the metal regulus obtained in the second trial, various observations can be made. Beside a high Fe and a rather low C content, especially the alloying elements deliver information concerning a possible selling price. Whereas contents of 0.023 % manganese and 0.007 % molybdenum do not constitute a problem, different rules apply to components such as phosphor with 0.011 %, sulphur with 0.053 % and copper with 0.163 %. In the high quality steel section dealing with P still represents a challenging task that can only be dealt with by special and cost-intensive treatments. Similar thoughts appear for the sulphur contained within the product. Since the produced alloy should find its use directly in the steel industry, no additional desulphurization is supposed to happen. Therefore, low levels of S seem appropriate for the alloy's application.

In order to sell the iron alloy to the steel industry, the contained copper plays an important role. In general, Cu counts as an undesirable alloying element due to the fact that it has a negative effect on the hot shortness in continuous casting processes and that it reinforces the brittleness of different types of steel. However, there are some applications such as weatherproof steel or some corrosion resistant grades that need a small percentage of this alloying element. Therefore, the resulting iron alloy from the process that contains copper could economically be sold to the adequate segment.

Industrial data show a possible selling price of 200-300 EUR/t and accordingly 276-414 USD/t when using the mentioned exchange rate of 1.38 USD/EUR. These values signify an enormous range that mainly depends on the produced quality. If the obtained product meets the industry's quality requirements and aims for the maximum price, overall earnings of 9.853.200 USD/year are possible for an annual input of 70.000 t of Waelz slag. However, by producing an alloy that is too high in Cu or any other undesired element and hence only achieving a low quality article, the earnings for this segment drop to 6.568.800 USD/year which means an overall lost profit of 3.284.400 USD/year in comparison to the best case scenario.

The two presented aspects show that, nowadays, the European industry can only define itself through high quality products for which reason an efficient and elaborate quality management constitutes an indispensable sector within a company. The processes have to be standardized in order to provide a constant operation mode which is not error-prone and that guarantees a stable product quality. At the same time all persons associated with the project have to be made aware of the importance of this topic, so it becomes a natural factor in the production processes.

12 Future Prospects

The main technological as well as economic parameters for the realization of the new method for recycling Waelz slag have been presented and described in this work. However, there are still many facets that can be altered or modified for which reason the thesis displays a guideline for a possible investment decision.

In order to enhance the technological aspects, some more tests will have to be performed. Trying variable CH_4:O_2 ratios for the combustion at different times of the process will help to achieve a reduced coke input. The main objective will be to guarantee a constant carburization of the metal bath, so there is enough reducing agent present to obtain a reaction with ZnO and the iron oxides. Another interesting factor is represented by the quality of the produced pig iron as it supposedly finds its use in the iron and steel industry. Adaptations can be made by mixing additives into the process and hence altering the alloy’s composition. Since the accumulating slag does not affect the earnings due to the risk of landfilling, the question arises if the quality could permanently be influenced in a way that the material can be sold to the construction industry for purposes such as road building. Trials in the laboratory have shown that the recycling of Waelz slag is possible from the technological point of view, however, there still is enough scope to enhance the process and make it more efficient.

The calculation of the economic aspects serves as basis for the investment decision. As can be seen in the corresponding chapters, a positive net present value can be achieved for the project when working with realistic numbers. These base upon comparable tasks from the metallurgical industry, however, they only represent assumptions for which reason further investigation will have to be performed in order to obtain the correct result. Since factors such as expected costs and earnings are always afflicted with uncertainties, all final values only represent an approximation to the reality.

The next step of the project consists of designing a financing plan. While the funding is usually divided into an equity part that has a share of 15 % and a borrowed capital one with 85 %, the supply of liquid resources can vary in this case as Befesa already possesses various equipment regarding recycling processes. These decisions, however, are situated in the area of responsibility of the corresponding company. The thesis’ aim to enlighten the technological and economic aspects of the new recycling method of Waelz slag shows a positive outcome and leaves a fully functioning Excel file including all necessary calculation data as a result. If any aspect is varied or modified, the programme will recalculate the whole process and decide the profitability of the entire project.

13 Literature

[1] World Steel Association: World crude steel output increases by 3.5% in 2013, online address: http://www.worldsteel.org/media-centre/press-releases/2014/World-crude-steel-output-increases-by-3-5-in-2013.html (2014).

[2] Dvorak, Petr Ing. et al.: Utilization of zinc-bearing waste materials for electrolytic zinc production.

[3] World Steel Association: Steel and energy, online address: http://www.worldsteel.org/dms/internetDocumentList/fact-sheets/Fact-sheet_Energy/document/Fact%20sheet_Energy.pdf (2008).

[4] Ammann, Pierre: Economic considerations of battery recycling based on the Recytec process process.

[5] Schneeberger, Gerald Dipl.-Ing. et al.: Recycling residuals from the iron and steel industry, focusing on filter dusts.

[6] Krassnig, Hans-Jörg Dr.: The Influence of Scrap Quality on the EAF Process and the Generated Filter Dust.

[7] Karner, Wilhelm Dr.: De-Zincing of Thin Sheet Scrap.

[8] World Steel Association: Achieving the goal of zero-waste, online address: http://www.worldsteel.org/dms/internetDocumentList/fact-sheets/Fact-sheet_By-products/document/Fact%20sheet_By-products.pdf (2010).

[9] Das, B. et al.: An overview of utilization of slag and sludge from steel industries.

[10] Agrawal, A. et al.: Solid waste management in non-ferrous industries in India.

[11] Vegas, I. et al.: Construction demolition wastes, Waelz slag and MSWI bottom ash: A comparative technical analysis as material for road construction.

[12] Quijorna, Natalia et al.: Recycling of Waelz slag and waste foundry sand in red clay bricks.

[13] Barna, Radu et al.: Assessment of chemical sensitivity of Waelz slag.

[14] Rütten, Jürgen Dr.-Ing.: Various Concepts for the Recycling of EAFD and Dust from Integrated Steel Mills.

[15] Olper, M. Dr. and M. Dr. Maccagni: Zn Production from Zinc Bearing Secondary Materials: The Combined Indutec/Ezinex Process.

[16] Steinlechner, Stefan Dipl.-Ing. and J. Doz. Dipl.-Ing. Dr. mont. Antrekowitsch: Hydro- and Pyrometallurgical Options for the Upgrading of Low Grade Secondary Zinc Oxides.

[17] Bokányi, L. Dr. et al.: Do we need to decompose zinc ferrites of the EAF dusts?.

[18] Jha, M. et al.: Review of hydrometallurgical recovery of zinc from industrial wastes.

[19] Schneeberger, Gerald Dipl.-Ing. and J. Doz. Dr. Antrekowitsch: Characterization of Typical Dusts from Foundry and Steel Industry.

[20] Ruh, Andreas Dipl.-Ing. (FH) and T. Dipl.-Ing. Krause: The Waelz Process in Europe.

[21] Matthes, J. et al.: A new infrared camera-based technology for the optimization of the Waelz process for zinc recycling.

[22] Global Steel Dust: Recycling Hazardous Waste, online address: http://www.globalsteeldust.com/steel_dust_recycling (2014).

[23] Harz-Metall: Wälzbetrieb, online address: http://www.recylex-germany.com/de/hmg/waelzbetrieb (2014).

[24] Befesa: The Waelz Furnace Procedure, online address: http://www.befesa-steel.com/web/en/servicios/tecnologia/horno_rotatorio/index.html (2014).

[25] Meurer, Urban Dr.-Ing.: Gewinnung von Zinkoxid aus sekundären Rohstoffen - Neue Entwicklingen im Wälzprozeß.

[26] Befesa: Plant Locations, online address: http://www.befesa-steel.com/web/en/empresa/presentacion/localizacion/index.html (2014).

[27] Kazanbayev, L. and P. Kozlov: Research, development and implementation of processing oxidized zinc containing raw material for zinc and indium recovery at Chelyabinsk zinc plant.

[28] Offenthaler, Dieter Dipl.-Ing.: Pyrometallurgische Aufarbeitungsoptionen für basische Wälzschlacke (2010).

[29] Kozlov, P.: The Waelz Process , "Ore and metals" publishing house , Moscow (2003).

[30] Turan, M. et al.: Recovery of zinc and lead from zinc plant residue.

[31] Steinlechner, Stefan Dipl.-Ing and J. Doz. Dr. Antrekowitsch: Options for Halogen Removal from Secondary Zinc Oxides.

[32] Antrekowitsch, Jürgen Dipl.-Ing. and H. Dipl.-Ing. Dr.mont. Antrekowitsch: Dezincing of steel scrap.

[33] ZincOx: ZincOx Recycling, online address: http://zincox.com/about/process-flow-sheet.asp (2014).

[34] Paul Wurth: PRIMUS®, a new process for the recycling of steelmaking by-products and the prereduction of iron ore, online address: http://www.metal2014.com/files/proceedings/metal_02/papers/193.pdf (2014).

[35] Schenk, Johannes: Reduction Technologies for the Recycling of Iron and Steel Residues.

[36] Antrekowitsch, Jürgen Dr. and C. Dipl.-Ing Pichler: Alternative Verfahren zur Aufarbeitung von Stäuben aus der Stahlindustrie.

[37] J. Rütten: Application of the Waelz Technology on Resource Recycling of Steel Mill Dust.

[38] Hoy, Christian: Aufarbeitung von Reststoffen aus der Zinksekundärmetallurgie (2008).

[39] Pawlek, F.: Metallhüttenkunde, 230-237 , de Gruyter , Berlin, New York (1983).

[40] London Metal Exchange: Historical price graph for Zinc, online address: http://www.lme.com/metals/non-ferrous/zinc/#tab2 (2014).

[41] European Central Bank: Monetary Policy, online address: https://www.ecb.europa.eu/mopo/html/index.en.html (2014).

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